Impact of management practices on Minnesota's specialty crop production: From biochar to tillage practices

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Eric Paul Nooker

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Kurt A. Spokas, Advisor

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Dedication

This thesis is dedicated to my family and my farming ancestors.

Abstract

Climate fluctuations have always been a risk to our ability to provide adequate food for the increasing global population. To reduce crop production uncertainties in this variable climate, two management practices were examined: biochar application and conservation ridge tillage.

Different biochars, application rates, and soil types were evaluated for their effect on seedling emergence and plant growth of specialty crops. Increases and decreases were observed in seed emergence and plant growth rates from biochar amended soil in a greenhouse study. A slow pyrolysis corn cob biochar (5% w/w) improved seed emergence performance the greatest across five specialty crops in the 4 soil types, with increases in emergence ranging from 2 to 67%. Biochar weathering from previous trials also influenced plant growth responses, and eliminated initial negative growth effects. Yield from field plot studies were not significantly different between biochar and control treatments. No universal relationship between biochar and its impact on specialty crop growth were observed across different soil types. However, there was good correlation between the suppression in plant growth with lower availability of nitrate and higher amounts of sorbed organic compounds on the biochar. Biochar additions had the greatest positive plant impacts on

sandy textured soils with low initial soil fertility, which increased growth and soil moisture retention.

Secondly, the impacts of ridge and conventional tillage on the yield and quality of three sweet corn varieties, *Overland*, *Protégé*, and *Ambrosia* were investigated. *Protégé* had greater marketable yields when grown under ridge tillage compared to conventional tillage. During 2012, there were no significant differences noted between ridge and conventional tillage treatments. However, in 2013, ridge till increased cut corn yield and ear marketability compared to the conventional tilled plots, suggesting additional benefits that were not adequately captured in this 2 year study. This study suggests that increasing the soil moisture holding capacity (with biochar or other amendments) as well as utilizing ridge tillage offers a potential tool for agricultural production to buffer future climate uncertainties.

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Chapter 1.0 - Introduction

1.1 Climate Variability

Climate variability is a global-scale problem and has many broad reaching impacts, one of which notably is water use and availability (IPCC, 2013). Agricultural crop production will need to intensify in order to feed the current global population (Thornton et al., 2014). To reduce crop production risks, field management, crop selection, and soil fertilization practices will need to be modified to address these issues (Bozzola and Swanson, 2014; Smith et al., 2014; Wood et al., 2014). In particular, soil water and nutrient pools need to become closed loop cycles while balancing inputs and outputs, ideally coming from sustainable sources (Oktem, 2008).

Although thoughts of agricultural water-use are typically focused on more arid regions, such as the western US, irrigation use in Minnesota increased through 2011 (MASS, 2012). In 2011, there was a total of 1.2 million acres with 466 billion gallons of permitted irrigation well water use for agriculture, including wild rice production (MASS, 2012). This represents 36% of the total agricultural land in Minnesota being irrigated, which is above the US national average of 28% (Figure 1.1, MASS, 2012).

In addition to field crops, specialty crops grown in greenhouses also require water. The amount of water-use for greenhouse production is 2-3 orders of magnitude higher than field-grown crops, for the same yields (Ackerman and Stanton, 2011). This higher cost can be supported largely due to higher profits from growing specialty crops compared to traditional field crops (i.e., corn, soybeans, or wheat) (Parcell and Cain, 2014). The profits of growing specialty crops in greenhouses compared to fields depends

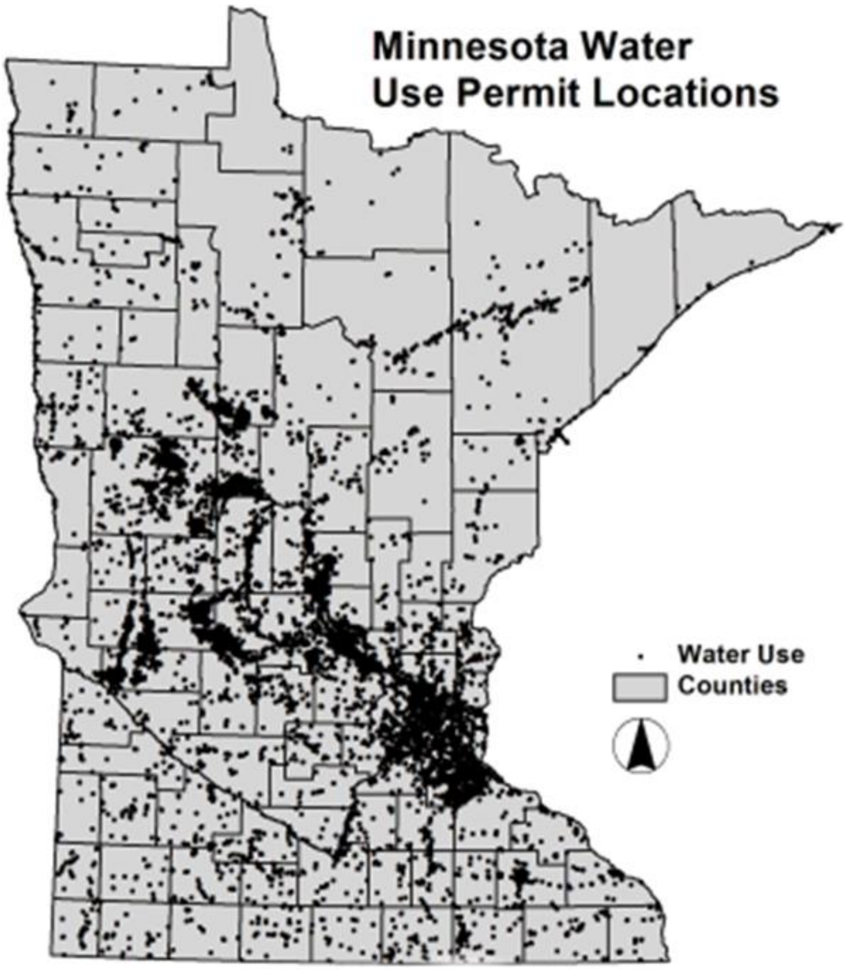

Figure 1.1. Illustration of the density of permit locations for consumptive irrigation wells for both crop and non-crop uses. This map was downloaded from: http://www.dnr.state.mn.us/waters/watermgmt_section/appropriations/wateruse.html.

on the specialty crop, but potentially can range from 1.5 to 4 times greater profit per acre in greenhouses (Cantliffe et al., 2008a; Cantliffe et al., 2008b). Greenhouses can control climate variability, but in the scenario of limited water availability field crops use less water.

Climate variability is something Minnesotan farmers cannot control. One of the critical aspects of climate change is the variability in the amount and frequency of precipitation (O'Gorman and Schneider, 2009). Without depending 100% on supplemental irrigation, or agricultural systems will have to adapt to these alterations. Therefore, other aspects of agricultural management need to be considered for improving long-term sustainable farming, including soil health, water availability, and crop rotation/selection. Improving soil chemical and physical properties is an intricate process, involving a complex balance of biotic and abiotic reactions. Soil formation is the net result of several interconnected factors: parent material, climate, biota, topography, and time (Buol et al., 2003; Jenny, 1946). More importantly, soil amendments can improve moisture holding characteristics, thereby offering the potential to buffer climate variability (Foley and Cooperband, 2002).

Soil amendments are known to influence soil fertility (Foth and Ellis, 1997). Soil amendments include, but are not limited to, conventional and organic fertilizers, microorganism inoculums (Jalauddin and Hamid, 2011), agricultural and industrial waste, (Anith et al., 2004), wetting agents (Sunderman, 2014), and biochar additions (Glaser et al., 2002). Among the existing soil amendments, biochar is extremely versatile and has the potential to be used for storing carbon in soil and simultaneously mitigating specific soil deficiencies. The particular traits of biochar that makes it appealing for this study are its slow microbial decomposition rate (Ameloot et al., 2013) and its ability to increase soil water holding capacities (Tryon, 1948). Therefore, biochar may be a powerful tool to improve agricultural productivity in variable climates.

1.2 Biochar Amendments

Biochar consists of plant or animal residue converted to charred biomass during pyrolysis, which is a chemical process in a heated, low oxygen environment (Atkinson et al., 2010). Biochar has been found to reduce fertilizer needs while maintaining or improving crop productivity (Biederman and Harpole, 2013; Crane-Droesch et al., 2013; Schulz and Glaser, 2012), and also has the potential to significantly improve the water availability and retention properties of both sandy and clay soils (Jeffery et al., 2011; Jha et al., 2010; Sun and Lu, 2014). Therefore, using biochar to target improvements in soil moisture characteristics has the potential to buffer crop production from climate variability. However, this is not a simple solution. Biochar physical and chemical properties vary depending on feedstock and pyrolysis conditions (Lattao et al., 2014; Mašek et al., 2013; Zhao et al., 2013) which can influence the emergence and growth of specialty crops in different ways (Rogovska et al., 2012; Solaiman et al., 2011). The original feedstock imparts the physical shape and appearance of the biochar particles. As an example, different types of biochar are shown in Figure 1.2.

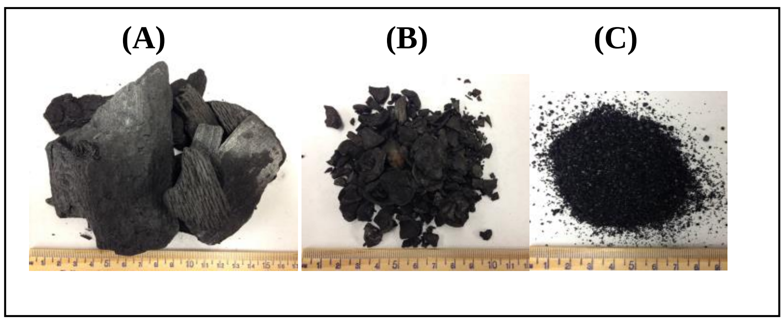

Figure 1.2. Photos of different biochar types are shown: (A) hardwood derived biochar, (B) a macadamia nut shell biochar, and (C) a distilled grain biochar. The ruler in each figure is the same (cm). This photo clearly shows that biochar physical sizes are highly variable.

One of the primary factors fueling the excitement over biochar is that increases in crop yields are sometimes observed when biochar is used as a soil amendment (Spokas et al., 2012). This is particularly the case with crop production in the tropics, with acidic, sandy soils (Jeffery et al., 2011). Overall research has shown that biochar can have variable effects on yield and plant growth, with no clear biochar property controlling these improvements across all biochar studies (Andrew et al., 2013). As a further complication, the impacts of using biochar as a soil amendment have not been extensively investigated in temperate cropping systems (Atkinson et al., 2010). Therefore, this study will examine adding different biochar types to upper Midwestern soils for impacts on various specialty crop seedling emergence, growth, and yield.

1.3 Ridge Tillage Management

Another crop management approach to help ensure agricultural sustainability and mitigate climate variability impacts on specialty crop production is soil tillage (Lal, 1991). Conventional tillage is the name given to the cultivation practices that includes moldboard plowing, chisel plowing, and rotary tillage (Table 1.1; Gajri et al. 2002). Typically, conventional tillage does not involve leaving any previous crop residue on the field during the preparation of the current year's field. On the other hand, conservation tillage is the name given to the practice of intentionally leaving at least 30% of the crop residue is left on the field (Walters and Jasa, 2014). This crop residue can provide beneficial services, such as reducing the amount of soil lost to erosion (Gajri et al. 2002). In other words, conservation till protects the environment while maintaining and improving soil health. This ensures long term sustainability, profitable crop production, and in some cases may enhance crop performance (Gajri et al., 2002; He et al., 2010).

Table 1.1 Overview of tillage methods.

Conventional tillage methods	Conservation tillage methods
Moldboard plow	No till
Chisel plow	Reduced till
Rotary till	Ridge till
	Mulch till
	Strip till

There are several different types of cultivation methods that are conservation tillage including strip till, no till, and ridge till (Table 1.1; Gajri et al., 2002). According to the Conservation Technology Information Center (CTIC), 40% of US field corn crop acreage are managed with some type of conservation tillage practice, which has slowly increased from 32% in 1989 (CTIC, 1989; CTIC, 2008). This growth has been attributed to the increased governmental support for soil conservation programs and incentives tied to the Food Security Act of 1985 (Walters and Jasa, 2014).

Of the conservation tillage methods, ridge till appears to be a promising but underutilized management practice that also improves soil water availably leading to increased crop growth and yield (Gajri et al., 2002; Servi-Tech and Hodson, 1991). Despite these documented advantages, as of 2008, less than one percent of agricultural acres in the U.S. are ridge tilled, and the total ridge till acreage has decreased by 38% since 1989 (CTIC, 1989; CTIC, 2008). This is due to complex cultural and scientific reasons (Reeder, 1990). The decrease in ridge till crop production acreage is concerning given the overall environmental advantages and minimal yield loss when switching from conventional to ridge tillage (Gajri et al., 2002; Servi-Tech and Hodson, 1991).

Ridge till is when row crops are planted on permanent ridges typically about 10-15 cm higher than the furrow (Gajri et al., 2002). The ridge tops are cut and the previous year crop residue is cleared off the ridge-tops and moved into adjacent furrows to make way for the new crop being planted on ridges (Figure 1.3; Walters and Jasa, 2014; Benjamin et al. 1990). Ridge till has the advantages of conservation tillage, yet there may be disadvantages including more time-consuming field operations, need for improved crop and residue management, pests and diseases can be harder to control with the additional crop residue left on the field compared to conventional tillage, field access will be limited (i.e. no driving across ridges with implements/wagons to damage ridges), and yield reductions may be possible as a function of the particular year's climate (Servi-Tech and Hodson, 1991; Reeder, 1990). Yet, the advantages of ridge till can outweigh the disadvantages, when considering long term sustainability (Hatfield et al., 1998; Pikul et al., 2001).

1.4 Soil Functional Zones in Ridge Tillage

The fundamental idea behind ridge tillage buffering climate variability is tied to the concept of soil function zones (Smith et al., 2014). Ridge tillage is assumed to create distinct areas in the field that support different soil-building processes as well as maintaining nutrient and water supply that are crucial to sustaining crop yield. This is seen as occurring in two primary soil functional zones:

1) Active turnover zones and

2) Soil building zones.

Figure 1.3 depicts these soil functional zones within a ridge till maize production system with a legume green manure or cover crop. Ridge tillage is a zonal soil management system in which soil disturbance occurs on permanent ridges that are cleared of crop residues at the time of planting, and re-hilled during crop development to help control weeds and soil erosion (Hatfield et al., 1998; Jordan, 1993). Combining ridge tillage and cover cropping practices creates the potential for significant improvements in the energy balance of maize production in the northern US maize belt (Rathke et al., 2007).

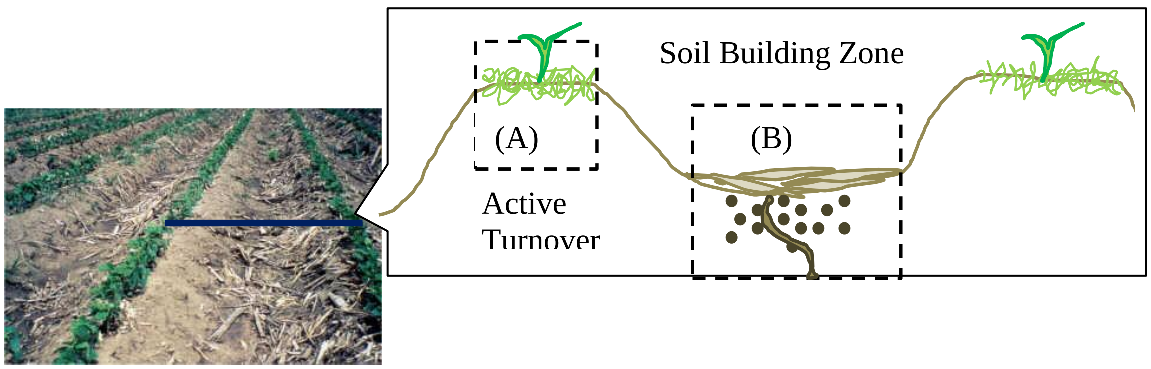

Figure 1.3. Illustration of the two zones of activity, the (A) a*ctive turnover* (crop growth) and (B) *soil building* (mineralization of residues) soil functional zones in ridge till management. This figure is modified from the one located at http://cropwatch.unl.edu/tillage/ridge.

Ridge tillage active turnover zones consist of the top 5 cm of the ridge that is cut and cleared of crop residue, biomass, and weeds (Figure 1.4). The limited soil disturbance in addition to the elevated ridges is hypothesized to create soil that is warmer, and conductive to moisture retention, thus promoting spring crop establishment (Hatfield et al., 1998; Kaspar et al., 1990). In addition, since the ridging will place newly decomposed residues around the plant roots, ridge tillage will also aid in the thermally-driven mineralization of organic N and P pools that should be synchronized with crop N demand (Honeycutt et al., 1994). Because the active turnover zone is located on the well-drained ridge, periods of soil saturation will be brief, due to topography influencing water distribution and ponding conditions, thus providing quicker soil drying during wet conditions (Benjamin et al., 1990). Additionally, during dry conditions, more soil moisture will be retained in the field as a whole due to reduced evaporative losses (Lal and Fausey, 1993). This will lead to lower potential for anaerobic site development and reduced emissions of trace greenhouse gases such as N_2O and CH_4 (Matson et al., 1998).

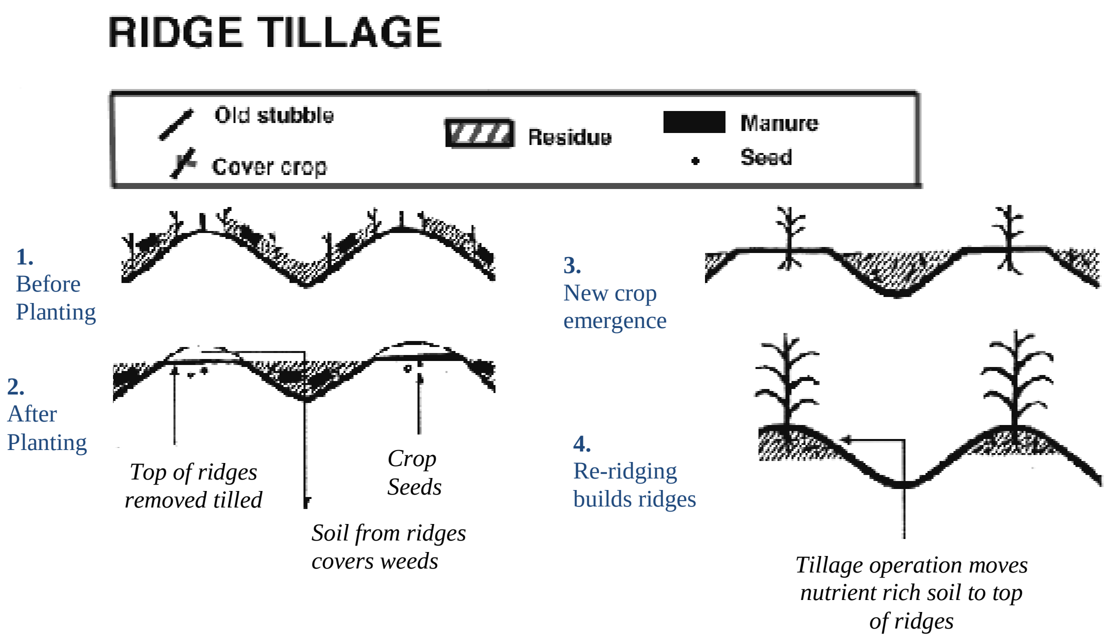

Figure 1.4. Conceptual processes occurring in various ridge tillage zones. Diagram edited from WSARE (1995).

Soil building zones will theoretically occur in the furrow areas of the ridge till system, where the soil microbes, residues, and weed biomass interact, which leads to the development of new soil and humidified organic matter. The decomposition of organic substrates from cover crops and weeds has been found to promote efficient carbon utilization by soil microbes, resulting in storage of C, N, and P in the form of microbial biomass and other nutrient pools (e.g., particulate organic matter) (Singh and Rengel, 2007). Approximately 4-6 weeks after planting, soil from the furrow is relocated to the ridge, supporting additional active turnover via additional microbial mineralization from organic nutrient pools. Soil disturbance is limited in both zones due to the lack of deep tillage, which promotes increased aggregation and potential carbon storage at undisturbed depths (> 20 cm) (Liebig et al., 1993). Thereby, these improvements in soil structural properties will promote increased water infiltration and water holding capacity and a general improvement in soil tilth (Karlen, 2013). A soil environment that maintains optimal moisture for plant growth, holds water during periods of low precipitation, and allows water to move deeply into the profile during high precipitation events will naturally promote optimal crop productivity while reducing opportunities for emissions of greenhouse gases under saturated/flooded conditions (Smith et al., 2003). Based on the rates of microbial reactions in the ridge till active zone and soil building zones, nutrient cycling and water use in ridge till production systems should be better suited to buffering the effects of variable rainfall and drought periods expected in future variable climates, than the current conventional production systems through improved soil moisture holding capacities (Ogle et al., 2005). However, it takes time for the soil to initially develop and reach optimal quality that can provide these environmental services.

Ridge till has been found to have no negative impact on yield and quality during an ideal growing season and also successfully enhanced cotton yield under excessive rain and cooler temperatures compared to conventional till (Mert et al., 2006). Also, ridge till has been found to increase mean maize yield and water use efficiency compared to conventional till in Northeast China (He et al., 2010).

1.5 Hypotheses Tested

This study investigates sweet corn production using ridge till in Minnesota. The majority of sweet corn grown for processing is produced in the southern portion of Minnesota, with the top three counties being Renville (12,400 ha planted 2011), Brown (3,035 ha planted 2011), and Dakota (3,360 ha in 2011) leading the state's 667,000 metric tons of processing sweet corn production during 2011 (MASS, 2012). Since 1960, Minnesota has been among the top three states producing sweet corn for processing (canned/frozen), and Minnesota currently produces 30% of the total processing sweet corn in the US (USDA, 2010a). Fresh market sweet corn is among the top three fresh market vegetable crop in terms of economic revenue generated in Minnesota (over $100 million of farm production each year) (NASS, 2013), and the state also ranks among the top ten fresh market sweet corn states in the US as of 2007 (NASS, 2007).

Crop production risks are a concern with current climate changes and variability. There are several specialty crop management strategies that can be utilized to ensure profitability while being conscious of water use and other environmental impacts. Using biochar as a soil amendment and utilizing conservation ridge till are only two possible strategies, both of which are potentially underutilized. By investigating these two management strategies, it is my hope to alleviate uncertainties, and produce results that can help specialty crop producers make sound management decisions.

H1: Biochar will impact specialty crop seed emergence, seedling growth, and yield, as a function of the biochar, amendment rate, soil, and crop interactions.

H2: Using ridge tillage will create advantages in terms of yield, kernel quality, and soil properties when compared to conventional tillage for three sweet corn varieties.

1.6 Thesis Format

I evaluated two management practices for the improvement of yield and growth of Minnesota specialty crops. The main focus was to examine soil modifications that have been used to increase soil moisture capacity and improve the sustainability of crop production in the presence of water availability uncertainties. Specifically, my research investigates two management practices, which will be described in the following chapters:

1) Chapter 2 - Impacts of biochar additions on specialty crop emergence, seedling growth, and initial biomass yield,
2) Chapter 3 - Sweet corn production under ridge and conventional tillage in Midwestern USA, and
3) Chapter 4 - Overall conclusions and future implication discussion of this research.

Chapter 2 – Impacts of biochar additions on specialty crop emergence, seedling growth, and yield in Midwestern USA

2.1 Overview

The impacts of soil biochar amendments on specialty crops were investigated through laboratory and field trials. Different biochars and soil types were evaluated while monitoring seed emergence of lettuce (*Lactuca sativa* L. cv. Black Seeded Simpson), radish (*Raphanus sativus* L. cv. Early Scarlet Globe), *Ambrosia* Hybrid sweet corn (*Zea mays* L. var. rugosa), cabbage (*Brassica oleracea* L. var. capitata L.), and spinach (*Spinacia oleracea* L. cv. Longstanding Bloomsdale) in the greenhouse. Additionally, crop yields in field trials of *Ambrosia* Hybrid sweet corn (*Zea mays* var. rugosa), potatoes (*Solanum tuberosum* L. cv. Red Ruby), and lettuce (*Lactuca sativa* L. cv. Black Seeded Simpson) were evaluated. A variety of responses were observed in biochar-amended soil seedling emergence and plant growth rates in the greenhouse study. Negative impacts of reduced seedling emergence were typically observed with the addition of a fast pyrolysis macadamia nut shell biochar. On the other hand, a slow pyrolysis corn cob biochar amended at 5% improved seedling emergence for specialty crops in 2 of the 4 soil types, with significant increases in seedling emergence ranging from 2-67%.

Biochar weathering by conducting sequential growth trials influenced seedling responses. Most notable was the disappearance of initial negative growth effects with the fast pyrolysis biochar. Plant growth was suppressed when there was lower nitrate availability compared to the control and with higher amounts of sorbed organic compounds on the biochar. These laboratory impacts were not observed in the field plots, which were statistically equal between biochar and control treatments. No universal relationship between biochar properties and its positive impact on specialty crop growth was observed in this study. However, biochar additions had the greatest positive plant impacts on sandy texture soils with low initial soil fertility. However, negative plant responses were correlated to the quantity of sorbed organic compounds or lower nitrate availability. These results suggest that specialty crop production on sandy soils could potentially benefit from biochar applications in Minnesota.

2.2 Introduction

Around half of the value of agricultural crop production in the US consists of specialty crops, which was estimated to have a retail value of ~$60 billion in 2005 (USDA, 2004). Specialty crops include fruits, vegetables, tree nuts, and nursery crops that are intensely managed (USDA, 2004). Due to the higher income resulting from specialty crops, more expensive specialized soil amendments can be targeted, with some of the initial targeted soil amendments focus on soil moisture retention improvements (i.e., Owen et al., 2007). Therefore, these factors also open the possible economic use of biochar in specialty crop production.

Biochar is degradable biomass that has been pyrolyzed into a more recalcitrant product of charred biomass to act as a carbon sequestration agent (Spokas et al., 2012). Biochar may provide benefits for specialty crop production by improving soil water retention, nutrient availability, microbial activity, and crop productivity (Jha et al., 2010; Spokas et al., 2012). However, the effects of biochar additions to both the soil and crops grown in amended soils are not fully understood, often with hormeosis like effects (Jaiswal et al., 2014).

Recent biochar research includes the interaction of biochar with the N-cycle (Deenik et al., 2010; Suddick and Six, 2013), its use as a carbon sequestering fertilizer (Magrini-Bair et al., 2009), and the use of biochar as a soil media used to raise nursery crops (Dumroese et al., 2011; Retan, 1915). Bioavailability and bioaccessibility of soil toxicities and pollutants with biochar amendments also has been studied (Ahmad et al., 2012; Khan et al., 2013). Research has been conducted to determine how biochar influences soil properties in greenhouses, fields, and urban environments (Beniston and Lal, 2012; Revell, 2011) and how it affects seed emergence and plant growth (Carter et al., 2013; Nelson et al., 2012; Oh et al., 2012).

However, the impacts of temperate specialty crop production with biochar soil amendments has not been investigated thoroughly despite the long history and growing interest of biochar use in agriculture (Güereña et al., 2012). Atkinson et al. (2010) analyzed ways that tropical biochar studies can be applied to temperate regions and concluded that while more information is needed, there is potential to develop specific biochars for targeted end uses to improve specific temperate soil quality for agricultural purposes. This has been reinforced by findings that biochar additions to fertile soils in temperate climates may not always improve crop productivity, but can improve soil quality with specific soil-biochar combinations (Güereña et al., 2012; Jones et al., 2012; Laird et al., 2010).

A delayed response in the stimulation or even a suppression of plant growth/ emergence can occur with biochar amendments (e.g., Major et al., 2010). This alteration in the response is considered to be a result of the weathering or aging of the biochar in which the biochar is physically, biologically, and chemically altered, thus impacting seed emergence and seedling growth. Deenik et al. (2010) hypothesized that this was due to the presence of volatile organic compounds sorbed to the biochar. In fact, it is known that pyrolysis of biomass materials generates chemical species that can be plant-microbe stimulants (e.g., increased seedling vigor, seed emergence, and root development) as well as chemicals that are plant inhibitors (Nelson et al., 2012). Keeley et al. (1985)

performed some of the very first experiments which documented increased seed emergence in the presence of wood derived chars. This stimulation effect was later observed in the water extract of various biochars, indicating that the actual stimulant chemical was water soluble (Keeley and Pizzorno, 1986) and postulated that the stimulant was derived from hemicellulose through pyrolytic heating above 175 ^{o}C. Further work has expanded our knowledge now to a wider range of potential chemical stimulants (e.g. acetone, cyanohydrin, glycolonitrile, ketones, aldehydes, karrikins, and mandelonitrile) (Footitt and Cohn, 2001; Keeley et al., 1985; Nelson et al., 2012; van Staden et al., 2004). On the other hand, other compounds sorbed on biochar are known to be inhibitory to plant growth, particularly naphthalene, and some extractable biomass compounds like vegetation-derived abscisic acid (ABA), terpenes, 1,8-cineole, bornane-2,5-dione, camphor, and β-thujaplicin (Brown and van Staden, 1997; Krock et al., 2002; Nelson et al., 2012). The types and amount of these compounds sorbed to biochar are highly variable (Spokas et al., 2011). In addition, these chemical signaling compounds are not the sole mechanism as other chemical and physical alterations also occur, specific to the particular soil, biochar, and plant types as well as the environment (Merritt et al., 2007).

Identifying the mechanisms of what causes this suppression in plant growth and managing this negative biochar effect is critical, since this will largely control the perceived economic value of biochar. This is an important facet for biochar utilization given the historical lack of predictive and economically meaningful yield increases justifying biochar use in agriculture (Davy, 1856).

Seed emergence tests are an efficient way to determine the effects of soil amendments on crop emergence and seedling growth. Fast, uniform plant emergence and seedling growth are early indicators of crop production success (Håkansson et al., 2011). Various amendments have been examined to increase seedling emergence including vermicompost, microbial inoculums, organic solid wastes, and biochar (Ievinsh, 2011; Jalauddin and Hamid, 2011; Zhang et al., 2013a). However, biochar properties vary depending on feedstock and pyrolysis conditions, which correspondingly influence the emergence and growth of seedlings in different ways (Rogovska et al., 2012; Solaiman et al., 2011; Deenick et al., 2010). This corresponds with the historical conclusion, that "using charcoal (biochar) as a fertilizer depends on circumstances" (Holbrook 1849).

To further investigate biochar amendments in temperate regions, trends in seedling emergence and growth across specialty crop species were monitored in a greenhouse study. A variety of biochar additions at different rates to different soil types were examined. In addition, companion field plots were established to examine the impact of one type of biochar on three different specialty crop yields. It was expected that while keeping environmental controls constant, different Midwestern soil and biochar interactions will reveal different trends among specialty crop seed emergence, seedling growth rates, and crop yield that could be correlated to biochar properties.

2.3 Materials and Methods

Seed emergence and growth of specialty crops were evaluated in greenhouse trials from 2010 to 2012. Various combinations of soil, biochar, and specialty crops (Table 2.1) were grown throughout the two years of the project in a greenhouse. The experimental design was a completely randomized full-factorial design. For each soil type (4 levels), there were 5 different specialty crops which had two between subject variables of biochar type (4 levels) and application rate (2 levels). Due to the large number of combinations [4 soils x 4 biochars x 2 levels x 5 crops x 20 plugs (minimum replication) ~ 4500 trials], these experiments were conducted over a period of 3 years.

2.3.1 Soils

Four different soils from the Upper Midwest USA with varying textural properties were used: Waukegan silt loam (Rosemount, MN), Vialas loamy sand (Hayward, WI), Hubbard loamy sand (Becker, MN), and Barnes-Aastad clay loam (Morris, MN) (Table 2.1). The soils were taken from the top 5 cm of soil and were ground and sieved to <5 mm. Only the top 5 cm of soil was sampled for this experiment. A commercial potting soil mix was also used as an additional growing medium to grow a limited number of specialty crops [Sun Gro Horticulture, consisting of Canadian Sphagnum peat moss, vermiculite, coarse perlite, starter nutrient charge (P, K, Ca, Mg, 100-125 ppm N, and gypsum) and dolomitic limestone]. The potting soil was not part of the factorial design, but rather was used in pair-wise comparisons with other soil types for the specific biochar and specialty crop.

Table 2.1. Overview of the factorial greenhouse experiments.

Soil Types	Biochar Types	Amendment Rates (w/w)	Specialty Crops
1) Waukegan silt loam	1) Macadamia nut shell	0%	Lettuce
[Rosemount, MN]	(fast pyrolysis)	5%	Radish
2) Vialas loamy sand	2) Wood pellet		Sweet Corn
[Hayward, WI]	(slow pyrolysis)		Cabbage
3) Barnes-Aastad clay loam	3) Corn cob biochar		Spinach
[Morris, MN]	(slow pyrolysis)		
4) Hubbard loamy sand			
[Becker, MN]			

2.3.2 Specialty Crops Examined

The five crops grown in the four Midwestern soils were lettuce (*Lactuca sativa* L. cv. Black Seeded Simpson), radish (*Raphanus sativus* L. cv. Early Scarlet Globe), *Ambrosia* Hybrid sweet corn (*Zea mays* L. var. rugosa), cabbage (*Brassica oleracea* L. var. capitata L.), and spinach (*Spinacia oleracea* L. cv. Longstanding Bloomsdale) (Albert Lea Seed; Albert Lea, MN). The plants were grown for about 50 d, and then removed.

Planting depth was based on seed supplier guidelines. The crops were chosen to represent a range of different specialty crops with different edible portions of plants; lettuce and radishes were specifically chosen since they have been previously used as indicators when testing for a response to biochar (Major, 2009). After 50 d, plants were carefully pulled out of the soil. For trials that observed a significant negative impact a new trial was planted in the same pot and soil mixture to examine the duration of this negative impact. The plants were grown under a uniform, controlled environment, in which no supplemental fertilizer was added. (Greenhouse conditions: 18-30 ^{o}C, supplemented with artificial light on cloudy days and 12-14 daylight hours). The plants were watered three times per week, in which the seedling emergence was monitored. The seedlings were measured for plant growth approximately once a week. Two to three seeds per pot were planted. If multiple seedlings emerged then seedlings were thinned to one per pot. To accommodate the various plant species, a combination of containers (D-40; 40 in^3 volume; Stuewe and Sons, Tangent, OR) and 288 plug trays (Model # 720528C -- PL-288-1.25; T.O. Plastics, Clearwater, MN) were used. Twenty to 100 individual replicate plugs were used to assess overall emergence rates, which were then converted to a emergence percentage (%) based on the initial number of pots planted. Plant growth parameters were recorded on at least 10 individual plants per treatment.

2.3.3 Biochar

Three different biochars were used in this greenhouse study: macadamia nut shells (ground and sieved to <5mm, 550 ^{o}C; fast pyrolysis), wood pellets (slow pyrolysis; 500-600 ^{o}C; sieved <5 mm), and corn cob (slow pyrolysis; 500-600 ^{o}C; sieved <5mm). These biochars were created with different pyrolysis units (Table 2.1). The biochar was mixed into the Midwestern soils based on percent weight fraction (w/w) at 0 and 5%. The biochars were analyzed pre- and post-growth (sorted from the soil by hand) to compare the amounts of sorbed organic compounds using a headspace thermal desorption technique following the method outlined in Spokas et al. (2011).

2.3.4 Field Plots

The field trials were located in Rosemount, Minnesota at the University of Minnesota Rosemount Research and Outreach Center. The soil at the experimental site is Waukegan silt loam (fine-silty over skeletal mixed, super active, mesic typic Hapludoll) containing approximately 22% sand, 55% silt, and 23% clay with a pH (1 : 1 H_2O) of 6.4, 2.6% total organic carbon, slope <2%, and a field capacity moisture content (−33 kPa) of 14.8% (w/w).

The field experiment was a randomized design with three replicates. Each plot was 3.0 × 3.0 m and received no supplemental irrigation or fertilization. Macadamia nut shell biochar was manually applied to triplicate plots at a rate of 22,000 kg ha $^{-1}$ acre and incorporated via rototilling to a depth of 15 cm. This particular biochar was selected based on the negative plant growth observed in the greenhouse results.

The yields of *Ambrosia* Hybrid sweet corn (*Zea mays* var. rugosa), potatoes (*Solanum tuberosum* L. cv. Red Ruby), and lettuce (*Lactuca sativa* L. cv. Black Seeded Simpson) were evaluated in these field trials over two years (Albert Lea Seed; Albert Lea, MN). The corn and lettuce seeds were spaced as specified by the supplier. The potatoes were hilled and evenly spaced within each plot.

2.3.5 Statistics

Results for seedling emergence are expressed as the number of emerged plants, normalized to 100. Seedling growth results were arithmetic means of total plant growth measured from the soil surface to the highest point of the plant and averaged by species. R (R Core Team, 2014) and JMP (SAS, 2012) were used for data analyses. Data was analyzed using an analyses of variance (ANOVA) procedure to test for statistically significant differences using 95% confidence interval ($P<0.05$) between the control and each biochar amended soil seedling emergence and plant growth (R Core Team, 2014). Pair-wise comparisons were performed for the soil data analysis to assess differences in biochar addition across the different soils for a given biochar and specialty crop combination.

2.4 Results

2.4.1 Greenhouse Seed Emergence

The results for the greenhouse experiment will be described grouped by soil type.

- Waukegan silt loam- Wood pellet biochar was the optimal combination with Waukegan silt loam soil (Table 2.2). This amendment level resulted in significant increases in emergence for lettuce (6%), sweet corn (11%), cabbage (18%), and spinach (24%) when compared to the unamended control soil. Corn cob biochar increased lettuce emergence by 6% and macadamia nut shell biochar increased spinach emergence by 12%. On the other hand, macadamia nut shell biochar amended at 5% resulted in decreases in emergence for lettuce (50%), sweet corn (26%), and cabbage (27%).

- Vialas loamy sand- Wood pellet biochar resulted in the best seed emergence performance (Table 2.3) with significantly greater seed emergence of sweet corn (11%), cabbage (21%), and spinach (89%). The corn cob biochar amended Vialas loamy sand was effective with enhancing emergence of lettuce (67%) and spinach (2%). Conversely, the corn cob amendment suppressed sweet corn emergence by 9%. Macadamia nut shell biochar resulted in decreases in seed emergence in radish (26%), sweet corn (11%), and cabbage (29%).

Table 2.2 Impacts of various biochars on seed emergence in Rosemount, MN soil. Results were normalized to 100.

Biochar	Amended Amount	Lettuce	Radish	Sweet Corn	Cabbage	Spinach
Control	0%	77.8	89.3	89.4	77.3	76.5
Macadamia nut shells	5%	27.8*	74.4	63.1*	50.0*	88.2*
Wood pellet	5%	83.3*	79.4	100.0*	95.4*	100.0*
Corn cob	5%	83.3*	N/A	82.0	N/A	89.5*

Notes: Asterisks are shown for statistically significant increases in seed emergence between the biochar and control treatment ($P<0.05$). N/A is shown for no available data.

Table 2.3 Impacts of various biochars on seed emergence in Hayward, WI soil. Results were normalized to 100.

Biochar	Amended Amount	Lettuce	Radish	Sweet Corn	Cabbage	Spinach
Control	0%	33.3	90.5	88.9	78.6	11.1
Macadamia nut shells	5%	30.0	64.6*	77.8*	50.0*	11.1
Wood pellet	5%	26.7	77.6	100.0*	100.0*	100.0*
Corn cob	5%	100.0*	100.0	80.1*	82.5	12.8*

Note: Asterisks are shown for statistically significant increases in seed emergence between the biochar and control treatment ($P<0.05$).

- Barnes-Aastad clay loam- The corn cob biochar amended to Barnes-Aastad clay loam significantly increased seed emergence for all the crops tested (Table 2.4): lettuce (9%), radish (33%), sweet corn (26%), cabbage (18%), and spinach (7%). Wood pellet biochar increased emergence of lettuce (43%) and spinach (2%). On the other hand, wood pellet biochar decreased seed emergence for radish (33%) and cabbage (24%). Also, macadamia nut shell biochar resulted in decreases in emergence of lettuce (43%), radish (33%), cabbage (49%), and spinach (2%).

- Hubbard loamy sand- Both corn cob and macadamia nut biochars amended at 5% significantly increased seed emergence of Hubbard loamy sand (Table 2.5). Macadamia nut shell biochar was effective in increasing seed emergence for all the crops except radish: lettuce (7%), sweet corn (18%), cabbage (16%), and spinach (12%). Corn cob biochar increased emergence for all the specialty crops except cabbage: lettuce (20%), radish (23%), sweet corn (33%), and spinach (17%). The macadamia nut shell biochar decreased seed emergence of radish by 23%. Also, the wood pellet biochar decreased seed emergence of radish (38%) and cabbage (21%) but increased seed emergence of lettuce (15%) and spinach (12%).

Table 2.4 Impacts of various biochars on seed emergence in Morris, MN soil. Results were normalized to 100.

Biochar	Amended Amount	Lettuce	Radish	Sweet Corn	Cabbage	Spinach
Control	0%	57.1	66.7	73.9	81.6	20.0
Macadamia nut shells	5%	14.3*	33.3*	55.4	32.7*	18.0*
Wood pellet	5%	100.0*	33.3*	64.6	57.1*	22.0*
Corn cob	5%	65.7*	100.0*	100.0*	100.0*	27.1*

Note: Asterisks are shown for statistically significant increases in seed emergence between the biochar and control treatment ($P<0.05$).

Table 2.5 Impacts of various biochars on seed emergence in Becker, MN soil. Results were normalized to 100.

Biochar	Amended Amount	Lettuce	Radish	Sweet Corn	Cabbage	Spinach
Control	0%	79.7	76.9	66.7	84.2	83.3
Macadamia nut shells	5%	87.0*	53.8*	84.5*	100*	95.3*
Wood pellet	5%	94.3*	38.5*	62.2	63.1*	95.3*
Corn cob	5%	100.0*	100.0*	100.0*	82.9	100.0*

Note: Asterisks are shown for statistically significant increases in seed emergence between the biochar and control treatment ($P<0.05$).

Overall Comparisons:

There was no single biochar that improved emergence and growth equally across all soil types compared to the control treatments (Table 2.6). The corn cob biochar most frequently increased seed emergence across all 4 soils and all 5 specialty crops, although not statistically significant when compared to the controls ($P>0.05$). On the other hand, macadamia nut and corn cob biochar decreased radish growth statistically compared to the corn cob treatment, but these differences were not significant compared to the control. Although not statistically significant, the macadamia nut biochar reduced the majority of the specialty crops yields, with the exception of spinach.

Table 2.6 Average normalized yields of the various specialty crops compared by treatments across all soils.

Biochar Treatment	Lettuce	Radish	Sweet Corn	Cabbage	Spinach
Control	1.00 A	1.00 AB	1.00 A	1.00 A	1.00 A
Corncob	1.62 A	1.16 A	1.17 A	1.03 A	1.22 A
Mac Nut	0.65 A	0.69 AB	0.90 A	0.72 A	1.05 A
Wood Pellet	1.20 A	0.69 AB	1.01 A	0.99 A	3.14 A

Note: Averages with different letters are statistically different ($P<0.05$).

2.4.2 Weathering of Biochar from Successive Greenhouse Cropping

No statistically significant trends were noticed with radish and spinach seed emergence in potting mix with and without ground macadamia nut shell biochar amendments (10% w/w) for the initial trial. Both radish treatments had a 94% emergence rate (control and biochar treatment). Spinach grown in potting mix had a 94% seed emergence rate, whereas spinach grown in the 10% (w/w) biochar potting mix had a seed emergence rate of 90%. These differences were not statistically significant ($P>0.05$).

Despite the similarity in seedling emergence, there were significant differences in seedling growth rates between treatments. An initial ground macadamia nut shell biochar (10% w/w) application was made to potting soil in which spinach was grown for a total of 5 sequential growth periods, ~50 days in length (Figure 2.1). During the first growth cycle, the biochar amended potting soil suppressed growth, compared to the control (Figure 2.1A). At the end of the first growing replication, the average spinach plant heights were 9.3 ± 2.1 and 3.8 ± 2.3 cm for the potting mix and biochar treatments, respectively. However, by day 24 of the second growth cycle (Figure 2.1B), the biochar amended spinach growth started to surpass the control potting soil mix. From this point on, the biochar amended spinach plant growth is equal to or outperforms the control for the remaining growth periods evaluated here (Figure 2.1C, D, and E). Additionally, the potting soil amended with biochar treatment had increased plant productivity compared to the control for rounds 2-5 (Figure 2.2). The second and third grow-out period biochar amended treatments were 200% greater than the control, and the fourth and fifth biochar amended treatment grow out periods had 100% greater plant mass than the control (Figure 2.2).

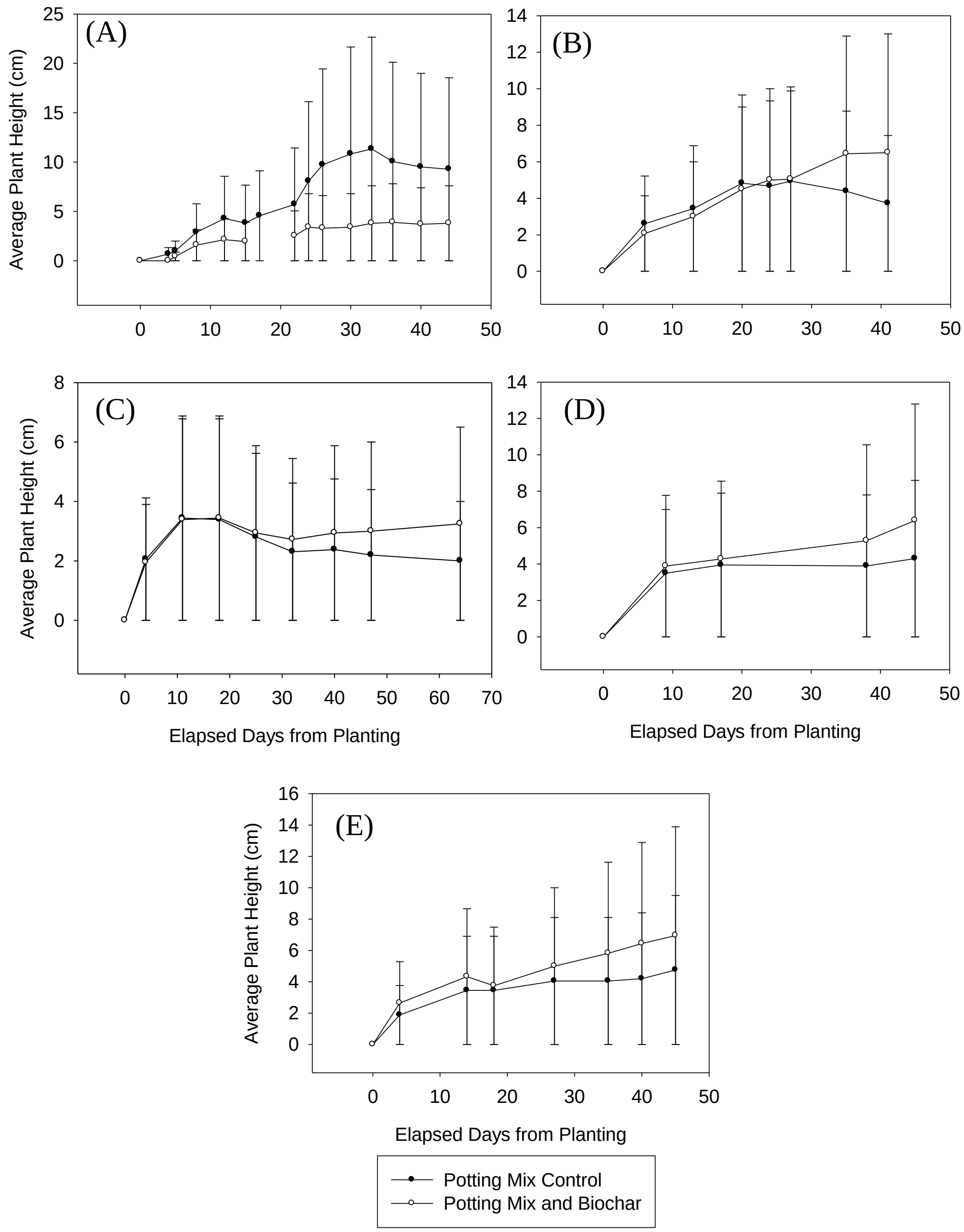

Figure 2.1 Average spinach plant height influenced by weathering effect of ground macadamia nut biochar (10 % w/w) mixed with potting soil, with (A) first 50 day growth period, (B) after second growth period, (C) after three growth periods, (D) after four growth periods, and (E) after five growth periods.

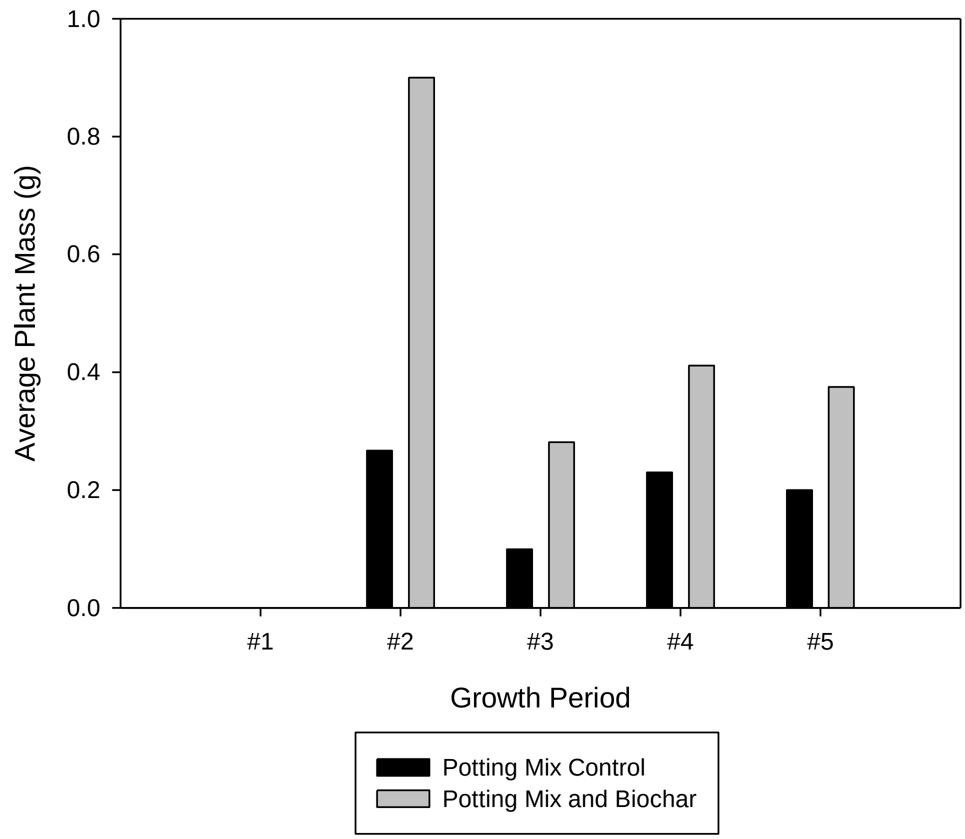

Figure 2.2 Average **s**pinach plant mass influenced by weathering effect of ground macadamia nut biochar (10 % w/w) mixed with potting soil, with second, third, fourth, and fifth consecutive 50 day growth periods in the same soil mixtures. (No data is available for the first growth period).

Figure 2.3 shows the relative height of radish over five consecutive growing periods, with the initial growth after the first planting (Figure 2.3A). There is a decrease in growth of the biochar amended potting soil compared to the control without biochar. At the end of the second round, at 41 DAP, the biochar amended potting mix treatment started to perform better than the control (Figure 2.3B). However, unlike the results observed above for spinach, this increased growth was not observed again until round 5, around 15 DAP, in which the biochar amended potting mix had greater average radish plant height than the control (Figure 2.3E). Additionally, based on radish plant mass, the control in round two had 50% greater average plant mass than the biochar amended potting mix (Figure 2.4). Yet, the above ground productivity of the biochar amended treatment in the third consecutive growth cycle was equal to the control (Figure 2.4). Round five resulted in the biochar amended treatment with twice the average plant biomass than the control, a 100% increase (Figure 2.4). However, no data for total plant biomass is available for rounds 1 and 4.

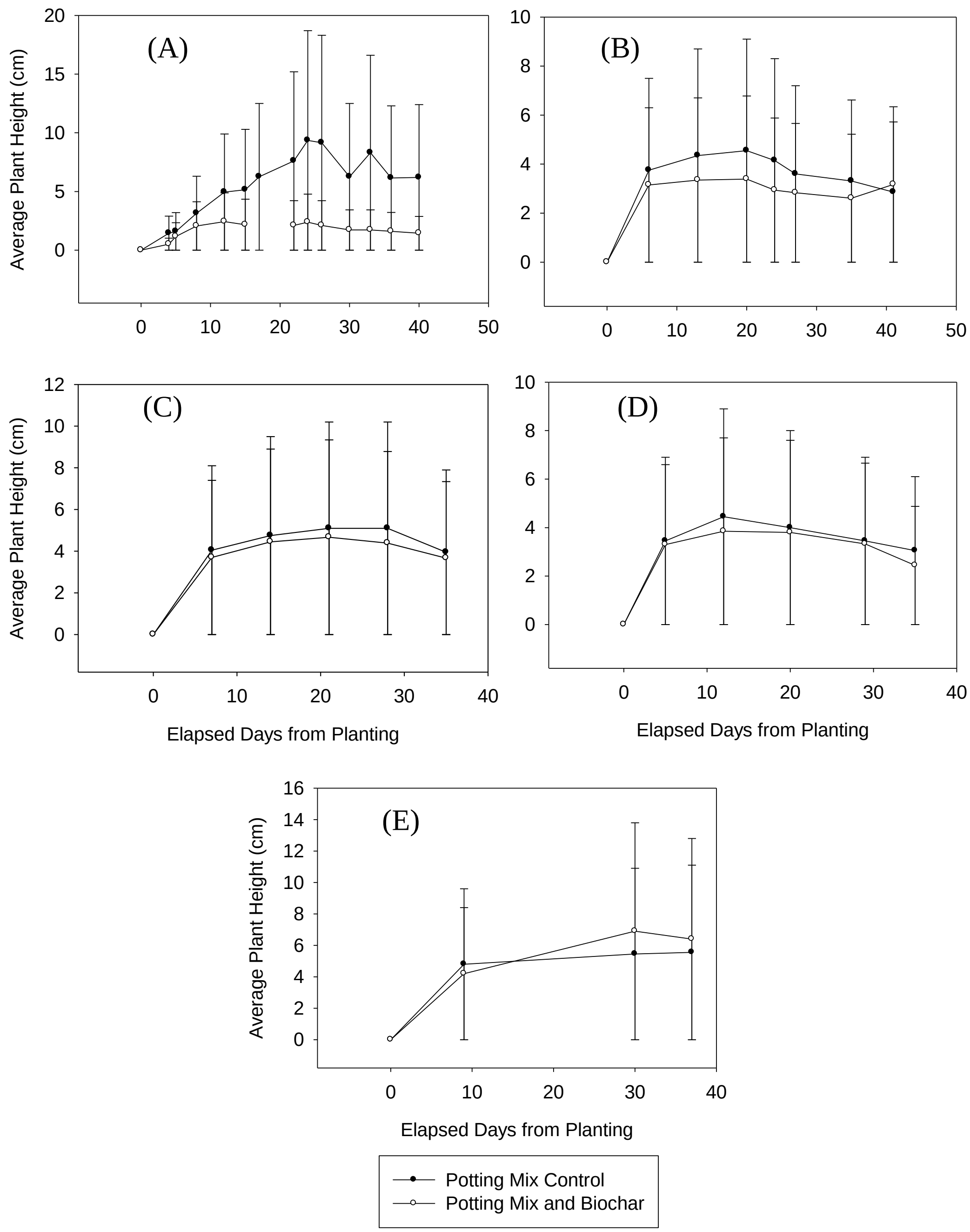

Figure 2.3 Average radish plant height influenced by weathering effect of ground macadamia nut biochar (10 % w/w) mixed with potting soil, with (A) first 50 day growth period, (B) after second growth period, (C) after three growth periods, (D) after four growth periods, and (E) after five growth periods.

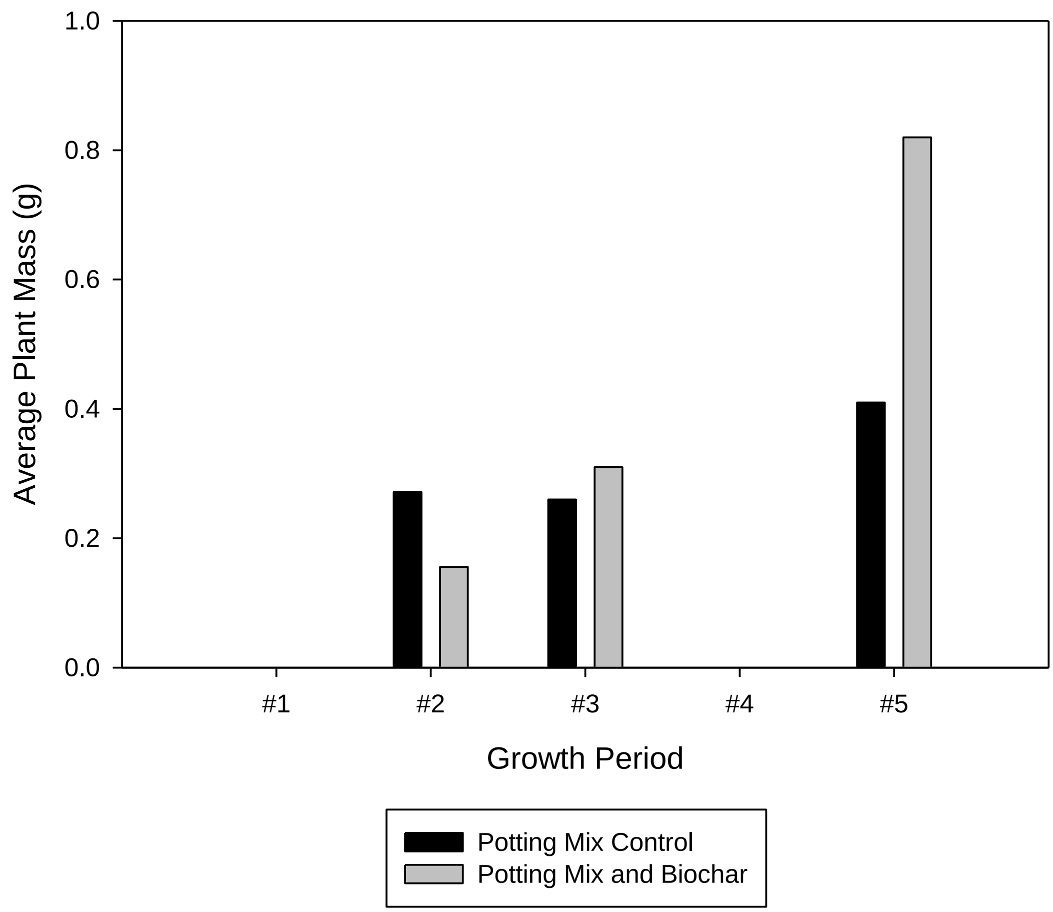

Figure 2.4 Average radish plant mass influenced by weathering effect of ground macadamia nut biochar amendment (10 % w/w) in potting soil mix with second, third, and fifth 50 day consecutive growth periods in the same soil mixtures. (No data is available for the first and fourth growth period).

There is a gradual disappearance of the suppression in the plant growth following macadamia nut biochar addition with consecutive growth cycles (Figure 2.2 and 2.4). There were also differences observed in some of the chemical and physical properties of the biochar during these subsequent growth trials.

The first noticeable difference was observed in the sorbed volatile signatures of the biochar. There was a pronounced decrease in sorbed organic compounds as a consequence of weathering (Figure 2.5). The original fresh macadamia nut biochar had a higher concentration and variety of compounds as indicated by the higher intensity and larger number of peaks in the chromatogram (Figure 2.5).

The peaks indicated in the chromatograms indicate differences in the individual compounds that were detected sorbed to the biochar. For the fresh biochar there were over 200 compounds detected (Figure 2.5A), while the weathered biochar only possessed 10 (Figure 2.5B). Complete identification of all these compounds was not possible. However, the GC-MS chromatograms do provide a clear indication of the alteration in the sorbed volatile and semi-volatile compounds on biochar.

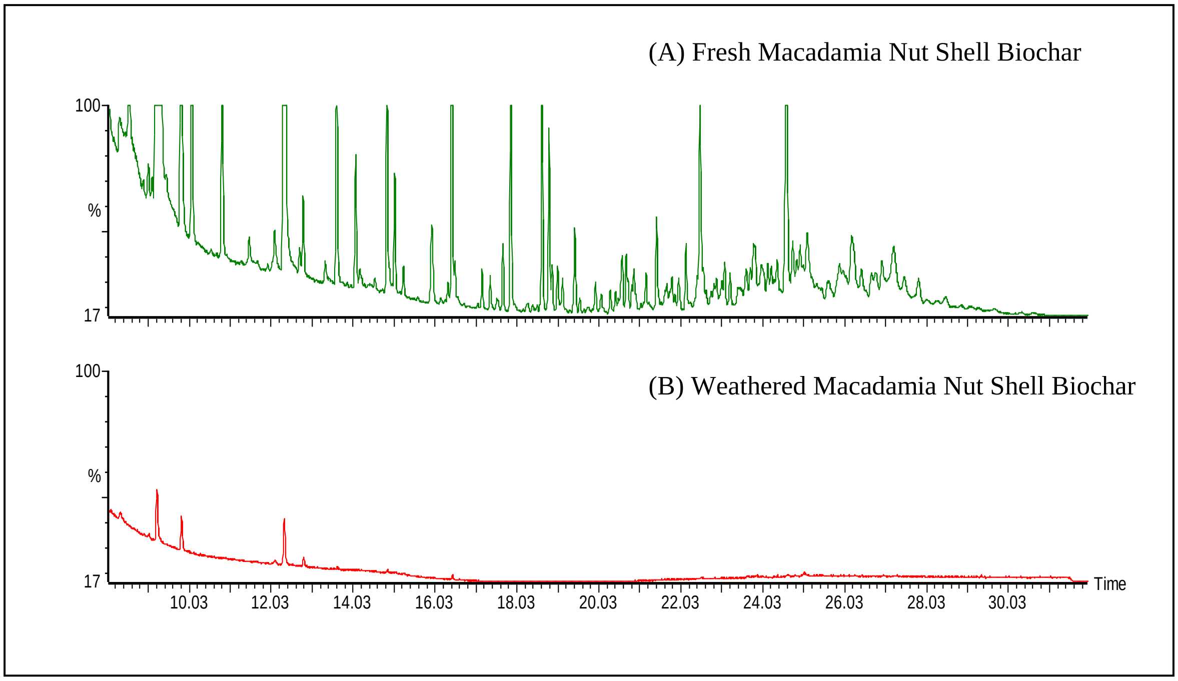

Figure 2.5. Difference in the thermal desorption headspace gas chromatography mass spectrometer chromatograms of (A) fresh macadamia nut biochar and (B) weathered macadamia nut biochar. The axes are scaled the same to allow comparison between the chromatograms.

In addition, by examining scanning electron microscope images of the original and the weathered macadamia nut biochar (Figure 2.6) there are other significant differences. In the fresh biochar, there is an organic film that covers the entire surface (Figure 2.6A). This organic film (i.e., absorbed organic compounds) could be responsible for the observed differences in the thermal desorption chromatogram of the initial biochar (Figure 2.5). Correspondingly, there is a very evident decrease in the amount and composition of the sorbed organics on the weathered macadamia nut biochar (Figure 2.5). This is also visible in the SEM imagery, where the weathered biochar now shows soil particles and other inorganic salts precipitates at the surface, with no indication of the organic film that was initially present (Figure 2.6B). This disappearance of the organic compounds has also exposed an increased in the available pore structure (Figure 2.6B). This difference in these sorbed compounds could be an important mechanistic linkage for the alteration in plant growth (Jaiswal et al., 2014; Deenik et al. 2010).

Furthermore, there are differences in the soil chemistry (comparing the initial and weathered soil + biochar samples; Table 2.7). The most noteworthy is the decreases in nitrate availability in the weathered biochar sample (at the conclusion of the first growth cycle). There is an increase in the pH, from 5.9 to 7 as a consequence of weathering. There are decreases in P and K, presumably due to leaching losses. There also is an increase in Fe and Cu, hypothesized to be due to the sorption of these cations from the irrigation water, although not directly confirmed.

(A)

(B)

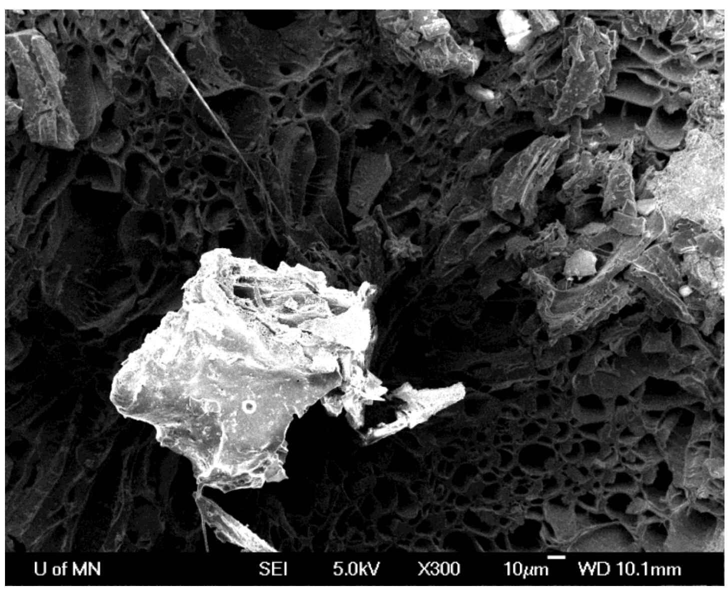

Figure 2.6 Representative SEM images of the (A) fresh fast pyrolysis macadamia nut biochar and (B) weathered fast pyrolysis macadamia nut biochar. Both images were collected at x300 magnification, 5.0 kV probe current, and the 10 μm scale bar is shown in each panel. (SEM images collected and provided by Edward Colosky - UMN).

Table 2.7 Potting soil weathering properties and nutrients.

Soil Property	Biochar State	
	Fresh	Weathered
pH	5.9 ± 0.1	7.0 ± 0.0
P	10.0 ± 2.0	2.7 ± 1.2
K	98.7 ± 26.5	31.6 ± 19.3
Ca	105.7 ± 7.2	91.3 ± 5.1
Mg	111.0 ± 12.2	56.1 ± 4.7
S	122.7 ± 10.1	53.5 ± 13.2
Na	42.4 ± 10.6	77.6 ± 26.1
Zn	3.6 ± 2.0	1.9 ± 1.8
Mn	6.8 ± 5.5	9.0 ± 1.1
Fe	16.6 ± 7.1	26.5 ± 2.7
Cu	0.7 ± 0.7	2.3 ± 0.5
B	0.1 ± 0.1	0.2 ± 0.1
Al	3.0 ± 2.8	3.8 ± 1.3
Cl	-5.3 ± 9.2	57.6 ± 11.6
Total N (ppm)	58.1 ± 8.7	2.3 ± 1.2
Ammonium-N (NH_4^+)	1.0 ± 1.1	0.3 ± 0.2
Nitrate-N (NO_3^-)	57.1 ± 9.0	2.0 ± 1.4

2.4.3 Rosemount, MN Field Plot Specialty Crops

Contrary to the observations in the greenhouse, there were no statistically significant growth differences observed among lettuce and potato yields in the field plots over the 2 years of this study (Figure 2.7 and 2.8). There was no significant difference between the control and biochar plots in potato (Figure 2.7) and lettuce yield (not shown). In 2011, 95% of the seed potatoes sprouted in both the control and macadamia nut biochar amended soil. In 2012, 100% of the seed potatoes germinated in both treatments. On the other hand, there were significant suppressions in the total cut corn yield as a function of biochar treatment in 2011 (Figure 2.8), but these differences were not observed in 2012.

The data here supports the concept that the sorbed organics is one potential mechanism for this interaction and reduction in seedling growth. Historically, certain compounds from plant extracts have been used as pesticides (i.e., Yang and Tang, 1988). Hypothetically, sweet corn could have a higher sensitivity to the specific allelochemical on the biochar than lettuce or potatoes due to the lack of yield differences in the treatment for the other specialty crops in 2011. The fact that the reduced germination impact was not observed in 2012 does suggest the potential to remedy the negative growth response of this macadamia nut shell biochar by weathering, which was also observed in the greenhouse experiments. Contrary to the observations here, typically seed size is correlated with resistance to allelochemicals (Heisey, 1990). Therefore, the exact mechanism cannot be conclusively confirmed.

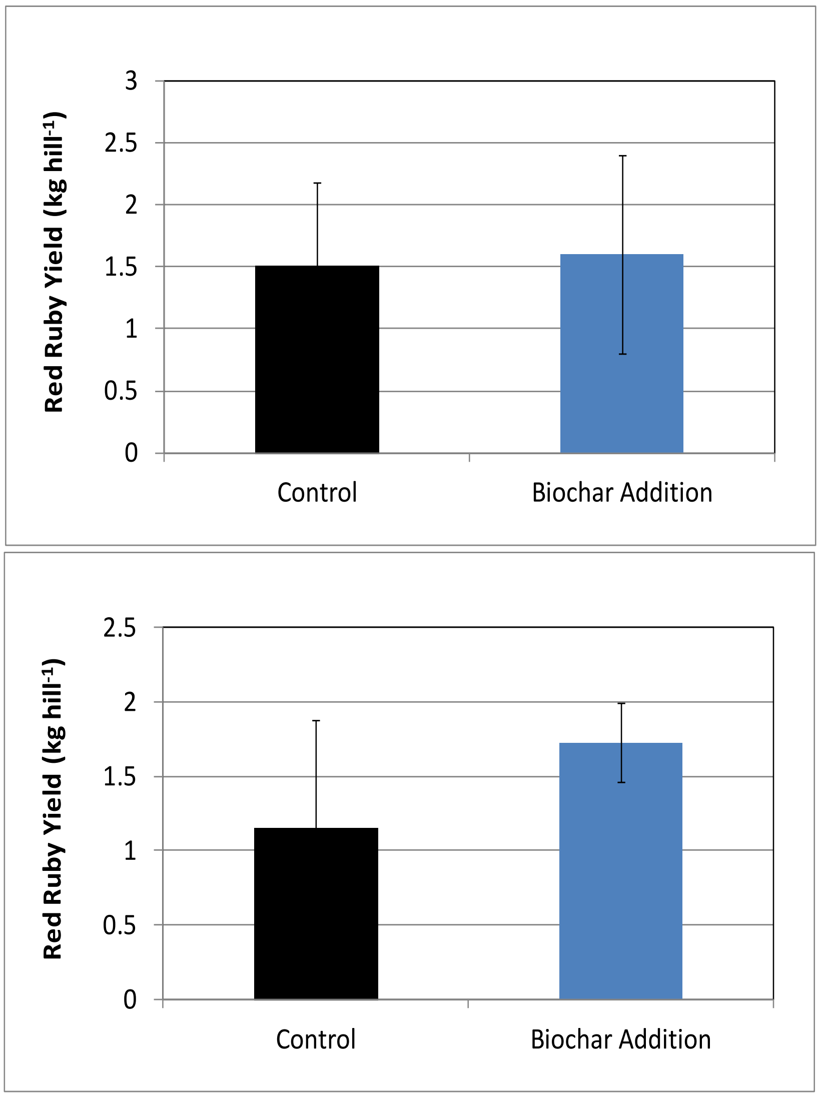

Figure 2.7 *Solanum tuberosum* potato yield in 2011 (top) and 2012 (bottom) in field plots at Rosemount, MN, with macadamia nut shell biochar additions (22,000 kg ha $^{-1}$).

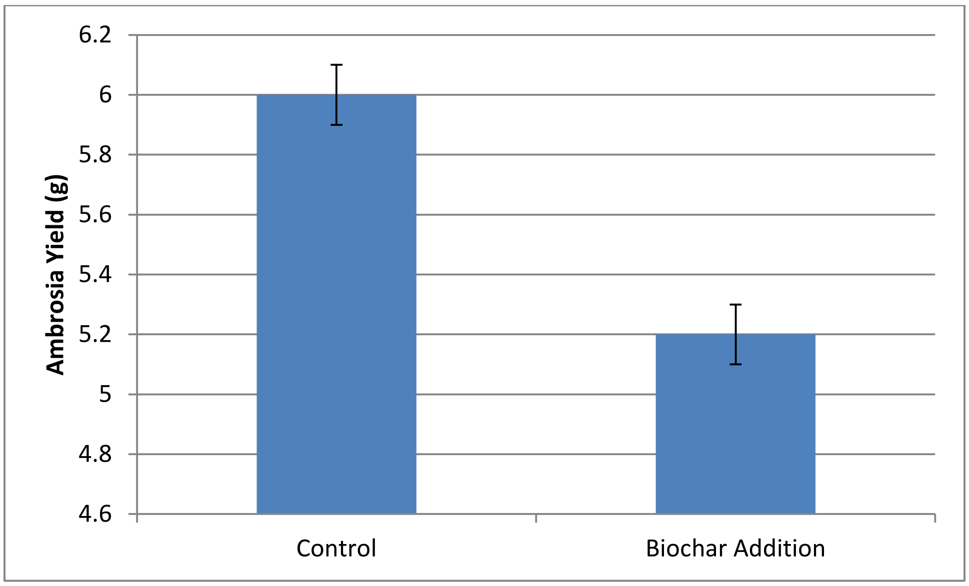

Figure 2.8 *Zea mays* L. var. rugosa sweet corn yield base on a 10 ear sample in 2011 field plots at Rosemount, MN with macadamia nut shell biochar additions (22,000 kg ha^{-1}).

2.4.4 Soil Analysis

In order to assess whether the differences between the field and greenhouse results were tied to soil nutrient differences, the soil from the greenhouse and field plots were analyzed for typical soil nutrients (macro and micro) before and after macadamia nut biochar addition. There were few differences between the greenhouse and laboratory soils. Typically, this biochar addition increased soil organic matter, calcium, potassium, extractable nitrate, and reduced iron, copper, and sulfur contents (Table 2.8). The differences observed here in the nutrients between the field and greenhouse are not sufficient to cause the drastic differences in plant growth that were observed in the greenhouse studies.

Table 2.8 Soil properties and nutrients of Rosemount, MN soil comparing field and greenhouse with macadamia nut biochar.

Soil Property	Greenhouse		Field	
	Control	5% (w/w)	Control	Field Biochar Addition (22,000 kg ha^{-1})
Organic Matter	4.6 ± 0.3	5.0 ± 0.0	6.4 ± 1.6	4.5 ± 0.0
Cation Exchange Capacity	16.0 ± 1.3	16.8 ± 0.0	11.3 ± 0.4	11.3 ± 0.4
pH	6.3 ± 0.3	6.2 ± 0.0	6.1 ± 0.0	5.7 ± 0.0
Buffer pH	6.7 ± 0.0	6.6 ± 0.0	6.7 ± 0.0	6.6 ± 0.0
P	51.5 ± 12.0	56.0 ± 0.0	47.0 ± 11.4	71.0 ± 0.0
K	150.5 ± 7.8	172.0 ± 0.0	166.3 ± 59.7	251.0 ± 0.0
Ca	2500.5 ± 95.5	2613.0 ± 0.0	1807.0 ± 431.5	2297.0 ± 0.0
Mg	517.0 ± 14.1	520.0 ± 0.0	464.3 ± 73.4	490.0 ± 0.0
S	12.0 ± 0.0	12.0 ± 0.0	18.0 ± 0.0	11.0 ± 0.0
Na	25 ± 0.0	22 ± 0.0	29.0 ± 0.0	28.0 ± 0.0
Zn	4.5 ± 0.0	4.3 ± 0.0	4.4 ± 0.0	3.9 ± 0.0
Mn	119.0 ± 0.0	104.0 ± 0.0	95.0 ± 0.0	67.0 ± 0.0
Fe	190.0 ± 0.0	168.0 ± 0.0	146.0 ± 0.0	149.0 ± 0.0
Cu	2.9 ± 0.0	2.5 ± 0.0	1.9 ± 0.0	1.7 ± 0.0
B	1.0 ± 0.0	0.9 ± 0.0	0.7 ± 0.0	0.5 ± 0.0

2.5 Discussion

2.5.1 Greenhouse Seed Emergence and Plant Growth

The trends observed with increases, decreases, and no differences among seed emergence are similar to previous biochar studies. Solaiman et al. (2011) found that low rates of biochar amendments of rice husks, metallurgical charcoal, and wheat chaff usually increased wheat seed germination, and higher biochar application rates had no effect or decreased germination. This could be due to a homeosis effect (Jaiswal et al., 2014), in which low concentrations of a chemical can result in stimulation but higher concentrations reduce plant growth. Biochar can contain some plant nutrients and chemical compounds from the original biomass and compounds created during pyrolysis may have impacted seed emergence in positive or negative ways in this greenhouse study, similar to the research on compounds in wood smoke (Nelson et al., 2012; Spokas et al. 2012).

The suppressed emergence of plants grown in the fast pyrolysis macadamia nut shell biochar treatment was a fairly consistent trend, among 3 of the 4 soil types and 4 out of 5 specialty crops (Table 2.6). Consistent with other recent research into the impact of fast pyrolysis biochars, there is the potential for negative effects on plants (Deenik et al., 2010; Keeley et al., 1985; Keeley and Pizzorno, 1986). This research also clearly showed that this impact quickly dissipates, and demonstrates that this negative impact on plant growth can be easily removed from biochar. This was demonstrated here through a headspace thermal desorption technique, where the biochar were analyzed pre- and post-growth to compare the amounts of sorbed organics. As can be seen in Figure 2.7, there is a significant decrease both in the quantity and number of different compounds comprising the sorbed species on biochar before and after growth trials. These results are in agreement to the reduction in sorbed organic compounds as a function of composting (Borchard et al., 2014), as well as the disappearance of the suppression in emergence observed by Rogovska et al. (2012) with successive rinsing.

Corn cob biochar appeared to promote the most consistent positive emergence and growth universally (Table 2.6). However, the one species that was not stimulated by the corn cob biochar universally was sweet corn (Table 2.2). This could be due to some allelopathic chemicals that are present (sorbed) on the corn cob biochar (Lehmann et al., 2011; Ni et al., 2011; Rogovska et al., 2012). This data suggests the use of a different biochar feedstock for the particular crop of interest, since this practice would remove the potential carryover of allelopathic compounds in the biochar.

The larger percentages of benefit (>20% plant emergence improvements over the control) were observed in the Hubbard loamy sand and Vialas loamy sand, which are both nutrient poor soils with sandy textures (Tables 2.3 and 2.5). Tomatoes grown in sandy soils with biochar added to the seedling root zones did have a significant resistance to wilting, which has potential to increase tomato production in drought-prone areas (Mulcahy et al., 2013). This impact is most likely one of altering the soil physical arrangement and soil texture. Soil type, especially coarse soils amended with biochar, has been found to have a significant effect on the seedling development (Tryon, 1948). This coarse texture interaction was also highlighted in a recent meta-analysis of biochar research (Jeffery et al., 2011), with biochar additions to coarse textured soils typically having the most beneficial impact. This increase could be due to the addition of pore sizes in the 0.2 to 30 µm in the post biochar amended soils (Figure 2.7). Tryon (1948) observed that the impacts of biochar additions were related to the original soil texture, with sandy texture soils possessing the highest boost in water holding characteristics. This is not surprising, since sand is dominated by large pores and holds very little plant avaible water compared to finer texture soils (Figure 2.9). Furthermore, plant growth is also impacted by differences in the soil moisture potential. For example, sunflower leaves grow best at soil matrix potentials between -1.5 to -2.5 bar, but the plant does not grow at soil moisture potentials less than -3.5 bars (Boyer, 1968). This demonstrates that even minor changes in the soil moisture potential above the wilting point still can have significant impacts on seed emergence and enhanced seedling growth rates.

This interaction with soil moisture and soil moisture potential could be an important mechanism to the observed differences in plant growth, particularly since soil moisture alterations also impacts the availability of soil nutrients to the plant roots (Veihmeyer and Hendrickson, 1950). Due to the distribution of particle sizes, hydraulic properties of sandy soils can be impacted to a higher degree than loam texture soil following biochar addition (particularly of silt or clay sized particles). However, biochars are heterogeneous in chemistry, physical shape, and sorbed chemicals, thereby confounding our ability to have universal guidance for which biochar to use with which specialty crop and/or soil. Further understanding of the mechanisms behind these interactions will allow the prediction of consistent trends. From this data the alterations in the availability of soil moisture could be the dominant mechanism over soil nutrient improvements.

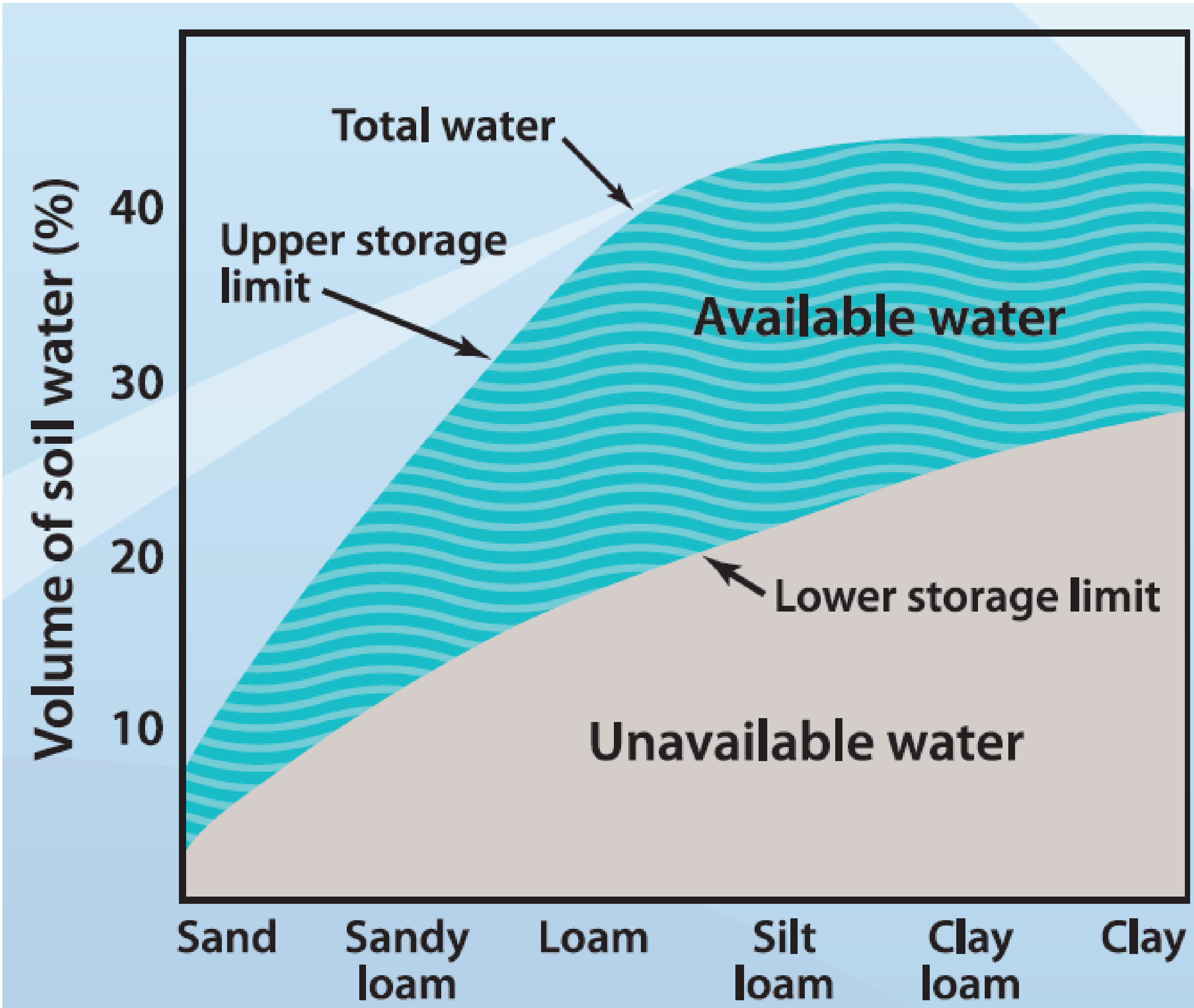

Figure 2.9. Alterations in the distribution of unavailable, plant available, and total water storage potential of different soil textures. Figure is taken from Kramer (1983).

2.5.2 Weathering of Biochar from Successive Greenhouse Cropping

There were two significant trends observed that were correlated to reduced plant growth in this study. The first was the disappearance of available nitrate (Table 2.7). Several studies have reported on the ability of biochar to reduce the leaching loss of nitrate in soil amended with biochar (Knowles et al., 2011; Prendergast-Miller et al., 2011; Raave et al., 2013; Ventura et al., 2013). It has been hypothesized that due to the increased sportive capacity of the biochar, nitrate was being absorbed to the biochar and thereby available to the plant at a later time (Clough et al., 2013; Hollister et al., 2013; Taghizadeh-Toosi et al., 2012). However, some recent studies have observed that this “sorbed” nitrate is not released following subsequent rinses with distilled water (Hollister et al., 2013) and may lead to reduced plant growth (Nelson et al., 2011). Historically, we know that biochar can occasionally sorb soil nutrients, which has been one of the difficulties in separating charcoal effects from nutrient deficiencies using charcoal in allelopathic chemical studies (e.g., Keeley et al. 1985, Inderjit and Callaway 2003). To overcome this nutrient sorption, it has been suggested to add fertilizer to the charcoal treatments to compensate for this effect (Putnam and Duke 1978), and has been echoed in more recent biochar studies (Nelson et al., 2011). In this study, supplemental fertilizer was not added and a decrease in available nitrate in the biochar amended potting soil mix was observed only in the initial 50 d period after application (Table 2.7). Recent results using biochar from hydrothermal carbonization (hydrochar) also observed reduced concentrations of mineral N in amended soil within the first week after incorporation (Bargmann et al., 2013). On the other hand, when there has been an increase in available nitrate following biochar application, plant growth has been stimulated (Zhang et al., 2013b). This increased nitrate is most likely from the biochar itself.

These same relationships of nitrate availability to plant growth were observed here. These complex interactions of biochar and inorganic N-forms deserves more scrutiny, particularly in light of abiotic pathways (chemodenitrifcation) that are not considered significant as its assumed that the N-cycle is dominated by denitrifying microbial pathways (Davidson et al., 2003; Willscher et al., 2013; Zhu et al., 2013).

The data of this study suggests that temporary biochar suppression of plant height can be eliminated with sequential growth periods or weathering. This indicates that negative effects from biochar additions are transient in nature. There have been hypotheses that biochar weathering in the field increases cation exchange capacity and surface oxygen moieties (Major et al., 2010), leading to increases in the CEC capacity and thus nutrient retention. Weathering of biochar has also reduced the mitigation effect of biochar on N_2O emissions (Spokas, 2013). This data shows that biochar weathering due to successive plant growth periods can be eliminated within 68 days for spinach grown in 10% w/w macadamia nut shell biochar. Rogovska et al. (2012) found that repeatedly leached biochar aqueous extracts used in seed germination tests significantly improved germination and corn seedling growth, presumably due to the reduced concentration of water-extractable inhibiting compounds. In a lettuce greenhouse biochar study, a similar recovery from stunting was attributed to the lettuce acclimating to the salts from the biochar as well as the decrease of soil salinity over time (Artiola et al., 2012). Beneficial microbe populations and hormesis (a favorable response to a slight amount of a toxin) were attributed to the enhanced plant performance of peppers and tomatoes grown in greenhouse biochar amended soils (Graber et al., 2010). Another study using hydrochar sugar beet pulp did not have any difference in beet seed emergence, and attributed early plant growth suppression to microbial N-immobilization due to the new carbon sources, which was later released in the growing season (Gajic and Koch, 2012). Additionally, other mechanisms are the result of phytotoxic, pollutant, and agrochemical compound sorption by biochar, allopathic soil and direct plant interactions with biochar (Lehmann et al., 2011). In actuality, the reduction of the temporary plant growth suppression associated with biochar amendments could be a combined effect of all of these potential suppression mechanisms.

In this research, we observed that the disappearance of the sorbed organics on the macadamia nut biochar (Fig. 2.6 and 2.7) was coupled to the loss of the suppression in emergence and growth. This can be an important factor due to the fact that the blocked pores are in the range of 1-15 μm (diameter estimation through SEM software), which are within the range of pore sizes to hold plant available water (0.1 to 30 μm). The size of pores can have a vital influence on whether or not bacteria can fit into the pore and how strongly water will be held within the pore. Therefore, if biochar adds pores <0.1 μm or >30 μm there is no improvement in plant available water (Hardie et al., 2014). In other words, each biochar has the capability to react differently, influenced by the combination of the soil, biochar, and plant interactions.

2.5.3 Rosemount, MN Field Plot Specialty Crops

The Waukegan silt loam soil used in this study is productive Midwest farmland and based on the specialty crop emergence and yield similarities, the soil was not greatly influenced by the biochar application. These findings are similar to a study with peppers grown in Virginia in a loam soil with poultry biochar amendments also had no significant improvement (Revell et al., 2012) as well as a lack of significant increases observed in a field study in California with walnut shell biochar (Suddwick and Six, 2013). Güereña et al. (2012) also observed no change in field corn growth with biochar addition to a fertile loam soil in New York.

However, Dou et al. (2012) found that biochar and fertilizer applied together could increase yield, sugar content, and visual appeal of sweet potato in soils with reduced organic matter and sandy texture. In addition, a majority of the existing biochar studies with large (>10% increase) in yield have been observed on coarse texture soils (Jeffery et al., 2011).

Thus, biochar has potential to be used in temperate Midwestern sandy soils that would benefit from improved soil moisture availability, but there is no evidence of benefits to plant yield in already existing productive soils. A low volatile matter biochar would be recommended.

2.5.4 Soil Analysis

The data on the soil chemistry pre- and post-biochar addition suggests that biochar does not significantly alter the soil nutrients, with only minor increases or decreases in a nutrient rich soil (i.e., Namgay et al., 2010; Hossain et al., 2010). However, the one observation that does deserve additional inquiry is that some biochar types reduce available nitrate (Nelson et al., 2011). Hossain et al. (2010) found that an increased P and N-availability as well as enhanced soil chemistry from sewage sludge biochar amendment improved the yield of tomatoes. However, the sewage sludge biochar most likely also contains inorganic-N forms. They found that tomatoes grown in the sewage sludge biochar amended soil had levels of heavy metals that are lower than the maximum permitted concentrations in food based on Australian standards (Hossain et al., 2010). The decrease in soil Cu at both biochar amendment rates (Table 2.6) could be due to plant uptake, leaching, or change in soil pH (Truog, 1947). Both Cu and B are trace minerals (Truog, 1947) and it is difficult to draw a robust conclusion from this soil data, but it does illustrate that there were no negative impacts. Additionally, it was surprising to find no significant nutrient differences based on soil weathering (Table 2.6), with the exception of the decreased nitrate concentrations.

2.6 Conclusion

The effect of biochar application and weathering on seed emergence, seedling growth, and crop yield depends on a complex interaction of soil and biochar properties, and the specialty crops grown. Negative emergence and seedling growth impacts were usually observed with fast pyrolysis macadamia nut shell biochar. The two slow pyrolysis biochars typically had positive impacts, with the corn cob derived biochar performing the best for improving seed emergence. However, seed emergence was increased most consistently in sandy textured soils. This supports the conclusion that biochar applications may increase crop productivity due to greater water availability and not as significant as altering total nutrient availability.

Chapter 3 – Sweet corn production under ridge and conventional till tillage in Midwestern USA

3.1 Overview

Soil tillage is a significant management decision, which has crop productivity impacts and also affects environmental quality. The traditional focus for ridge tillage use has been on reducing soil erosion. However, this chapter examines the potential for ridge tillage to be implemented as a management practice improving the resiliency of crops to climate variability. Specifically, this research examined yield and quality of three sweet corn varieties, *Overland*, *Protégé*, and *Ambrosia*, comparing the impacts of ridge and conventional tillage across two growing seasons.

There were significant differences observed for the two seasons in total and frequency of rainfall, thus capturing aspects of climate variability. Overall, there was a significant 17% increase in cut kernel yield resulting from ridge tillage when averaged across the 2 years and three varieties ($P<0.05$). This supports the conclusion that ridge tillage will lead to improved sweet corn yields in variable climates when compared to conventional tillage. On the other hand, differences in sweet corn kernel chemistry were more dependent on climatic differences than tillage type. There was no clear difference observed between tillage treatments and sweet corn kernel chemistry, but there was a significant difference as a result of the different years ($P<0.05$). Collectively these results do illustrate the potential beneficial use of ridge tillage to buffer sweet corn yield losses in the context of Minnesota's climate variability.

3.2 Introduction

Sweet corn is genetically derived from field corn (*Zea mays* subsp. *mays* L.) and was selected for a mutated recessive gene that allowed sugars to accumulate in the seed endosperm (Schultheis, 1998). Thereby, this mutation resulted in the sugary taste that resulted in the sweet corn name. Prior to the discovery of this "sugary" gene in the mid-1700s, *Zea mays* (field corn) was picked immature and cooked as a vegetable (Hansen, 2012), due to the softnesses and higher sugar content in immature kernels. Currently, there are two major end markets for sweet corn production. These are sweet corn grown to be processed prior to sale (e.g., frozen, packaged, canned) or sweet corn sold directly to fresh market. Sweet corn is the third most important processing crop in the USA following potatoes and tomatoes (Hansen, 2012). Since 1960, Minnesota has been among the top three states producing sweet corn for processing (canned/frozen) (USDA, 2010a). Specifically, Minnesota has accounted for 20% the processed sweet corn grown in the US in 1960, and this number has steadily grown to 30% in recent years. In 2009, Minnesota produced an estimated 980,000 short tons, which was valued at $97,545,000 (USDA, 2010b). Among fresh market vegetables grown in Minnesota, sweet corn is among the top three crops in terms of economic revenue generated (NASS, 2013). Minnesota also ranks among the top ten fresh market sweet corn states in the US as of 2007 (NASS, 2007).

Climate variability is something Minnesotan farmers cannot control. Therefore, other aspects of agricultural management need to be considered for improving long-term sustainable farming, including soil health, water availability, and crop rotations (Karl et al., 1995; Rose et al, 2001). Soil tillage is a significant management practice that impacts both crop production and environmental health (Karlen et al., 1994). While boosting crop productivity, cultivating the soil with conventional tillage can lead to negative impacts on the environment (Lal, 1991; Pikul et al., 2001). Furthermore, the weight of the machinery compacts the soil, potentially leading to a hard pan layer in the subsoil (Duttmann et al., 2014; Lal, 1985). By regularly mixing the soil, nutrients, and organic matter through tillage, the soil erodes more quickly than if the soil was not tilled (Lal, 1985). Storm water runoff and soil erosion have a profound impact on the environment (Hollinger et al., 2001), since fertilizers and chemicals are carried away with the flows, and eventually may lead to eutrophication in aquatic systems that can be located far distances from the original farm field (Young et al., 1989). A classic example is the dead zone in the Gulf of Mexico, which results partially from these dissolved nutrients from Midwestern agricultural practices that drain down the Mississippi River (McIsaac et al., 2001; Rabotyagov et al., 2014).

Previous studies investigating sweet corn grown under conventional tillage included yield impacts of cover crops (Cline and Slivernail, 2002; Mohler, 1991; Sarrantonio and Molloy, 2003), varying planting dates (Kwabiah, 2004; Williams, 2009a), weed competition (Mohler, 1991; Williams, 2009b), and the use of mulches (Kara and Atar, 2013; Kwabiah, 2004). Cover crops are successful in managing runoff, soil erosion, weed pressure, and crop diseases, while increasing soil fertility and environmental sustainability (Hoorman, 2009; Miguez and Bollero, 2005). However, cover crops can add to management challenges including additional labor and expense, may compete with the primary crop for nutrients and water availability, and occasionally introduce challenges such as new weed varieties (with cover crop seed) and attracting new pests and potential diseases (Curran et al., 2014; Hoorman, 2009). Earlier planting dates for sweet corn also may decrease yields, but this is not seen at later planting dates (June –July) (Williams, 2009a). It has also been observed that the risk of yield loss from weed competition is lower in later maturing sweet corn varieties (Makus, 2002; Williams, 2009b). Plastic mulches increase soil temperature, especially in the root zone, which leads to earlier harvest times for sweet corn compared to non-mulched plots (Kwabiah, 2004).

There are studies that examined growing sweet corn using conservation tillage such as strip till (Luna and Staben, 2002), minimum till (Ndon and Harvey, 1981), no till (Cline and Silvernail, 2002; Mohler, 1991), or a combination of conservation tillage practices (Petersen et al., 1986; Smittle et al., 1981). On the other hand, two studies were located that specifically investigated sweet corn yield with ridge and conventional tillage (Makus, 2000; Makus, 2002). In both studies, sweet corn was compared in a semi-arid subtropical environment. However, in these two studies, ridge till was not statistically different when compared to conventional tillage (Makus, 2000; Makus, 2002). However, this could have resulted from the supplemental irrigation, since there was no moisture stress. The majority of research on corn production with conservation tillage focuses on field corn (*Zea mays* subsp. *mays* L.) (i.e., Makus, 2002). There are a few studies from more arid countries that suggest that ridge tillage (or raised beds) promote higher yields in water stressed environments compared to other tillage/planting methods (Belachew and Abera, 2010; Arif et al., 2001; Siddique and Bakht, 2005; Bakht et al., 2011). Overall, a mix of yield advantages, disadvantages, and relatively no change have occurred with growing field corn under ridge tillage (Pikul et al., 2001; Rathke et al., 2007).

Ridge tillage management was first developed to combat soil erosion (Hatfield et al., 1998; Logsdon et al., 1993; Pikul et al., 2001). It has been observed that ridge tillage typically reduces soil erosion by 35-70% (Thapa et al., 1999). Although there were difficulties in the wide-spread adoption due to perceptions of uncertainties and greater crop management (Reeder, 1990), there have been reports of recent resurgence in China (Zheng et al., 2014). Its benefits will have to outweigh the negative aspects and perceptions of its use in order to be ultimately adopted by farmers (Reeder, 1990). Ridge tillage can lead to soil changes that improve the soil environment for crop emergence and early growth (Osman, 2014), which also improves long term environmental sustainability (Hatfield et al., 1998; Shi et al., 2012; Zheng et al., 2014). Therefore, ridge tillage can also be viewed as a potential tool to reduce climate variability risks, while simultaneously maintaining or increasing crop yield (Smith et al., 2014; Zheng et al., 2014).

Sweet corn yield ultimately depends on variety, tillage, soil nutrient and environment interactions. Optimum yields are achieved with judicious management practices and careful attention to genetic variety selection (Makus, 2002; Servi-Tech and Hodson, 1991). The aim of this study is to evaluate the impacts of ridge tillage on sweet corn production in Minnesota, by examining three different varieties of sweet corn, cut corn yield, as well as soil characteristics in field plots for 2 consecutive years. The overall hypothesis is that utilization of ridge tillage will lead to higher yields and increased kernel nutrients and sugars compared to conventional tillage for three different sweet corn varieties.

3.3 Materials and Methods

3.3.1 Location

Experiments were conducted during 2012 and 2013 at the University of Minnesota Research and Outreach Center in Rosemount, Minnesota (44°71’ N, 93°10’ W). Soil at the site is a Waukegan silt loam (fine-silty over skeletal mixed, super active, mesic typic Hapludoll) containing approximately 22% sand, 55% silt, and 23% clay with a pH (1:1 H_2O) of 6.4, 2.6% total organic carbon, slope <2%, and a field capacity moisture content (−33 kPa) of 14.8% (w/w). Plots were 4.6 × 12.2 m, containing six rows of plants (76.2 cm spacing) (Figure 3.1). The field was farmed with conventional tillage (chisel plow) with a corn and soybean rotation prior to the establishment of this experiment, and field corn was cropped the year before the sweet corn. During 2012, the area surrounding the plots was planted with soybean and during 2013 field corn was grown surrounding the plots. This field corn was separated by planting date (~2 weeks) to avoid cross-pollination risks in this experiment. However, individual sweet corn variety plots were not separated spatially or temporally, due to logistic constraints and then confounding planting date differences. Sampling occurred in the middle four rows to minimize this cross-pollination potential.

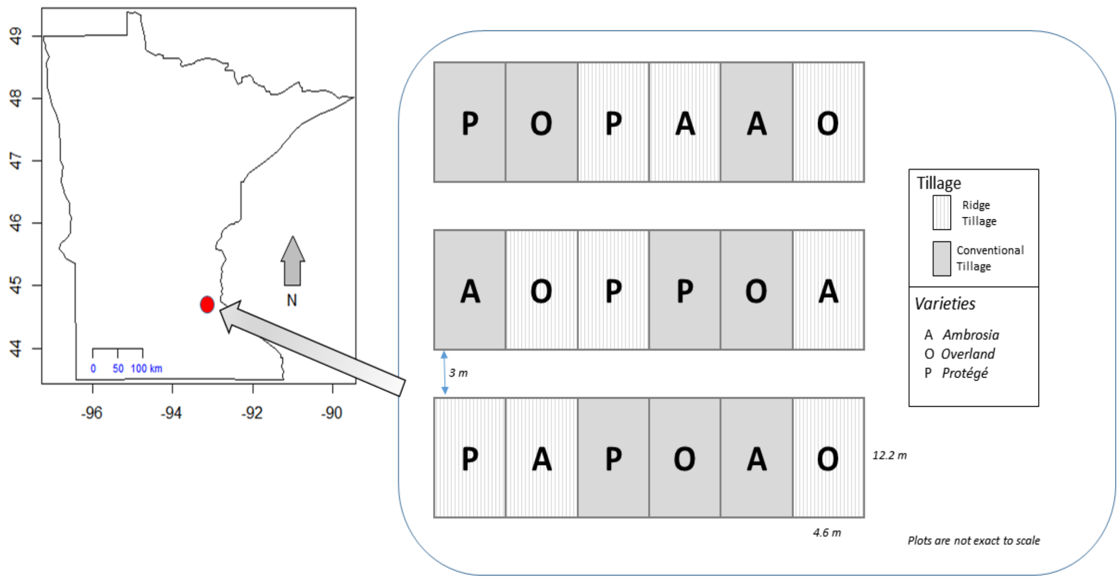

Figure 3.1 Graphical representation of the complete randomized layout at the Rosemount Research and Outreach Center at UMore Park located in Rosemount, MN (44.71°N, 93.10°W).

3.3.2. Experimental Design

The experiment was a randomized block design with 3 sweet corn varieties × 2 tillage treatments × 3 replications (18 plots total) (Figure 3.1), with tillage and variety as the main management factors and the blocking factor was the three replicates (Gomez, 1984). Individual plots were 4.6 × 12.2 m. Tillage treatments were either ridge or rotary tillage. Rotary tillage was chosen as a representative conventional tillage method due to the small plot size and the need to representatively handle the residue in the small plots. Ridge tillage was accomplished with a Hiniker 6000 Cultivator (Mankato, MN). Ridging occurred when the sweet corn was approximately 60 cm high in both years. The resulting ridge was approximately 20 cm high. The ridging was done on 27 July 2012 and on 26 July 2013, which corresponded to 35 and 30 DAP in 2012 and 2013, respectively. The plots were solely dependent on natural rainfall and received no supplemental irrigation. Following harvest, the top of the ridge was sliced which prepared the field for the next spring's planting surface. A total of 3 sweet corn varieties were examined: two processing sweet corn varieties: *Protégé* and *Overland* (shrunken-2, (SH2) type; Syngenta) and one fresh market variety, *Ambrosia* (sugar enhanced, (SE) type; Albert Lea Seed; Albert Lea, MN). These varieties were grown based on advice received from the local sweet corn industry (Syngenta) and supplemented by seed supplier and local farmer recommendations (Albert Lea Seed and Syngenta, personal communication June 5, 2012).

In 2012, the field was rotary tilled and the sweet corn was planted on June 22nd. In 2013, the sweet corn was planted on June 26th. All three sweet corn varieties were planted with a six row planter at 54,610 plants ha^{-1} density and a targeted 4.5 cm deep. Seeds were spaced at 24.1 cm, with rows every 76.2 cm. Pre-plant fertilizer (9-23-30) applied at 112.0 kg ha^{-1} was surface applied (broadcast) within one week of planting during both years, based on soil testing and recommend best practice guidelines for the region.

Due to the fact that weed pressure was not assessed in this experiment, weeds were controlled by chemical means to eliminate confounding impacts on tillage factors. A one-time application of N-(phosphonomethyl) glycine, glyphosate, was applied to all plots in both years (2012 and 2013), which occurred within one week after planting. There was severe weed pressure in 2013 which required an additional application of tembotrione (2-[2-chloro-4-(methylsulfonyl)-3-[(2,2,2-trifluoroethoxy)methyl]benzoyl]-1,3- cyclohexanedione; Laudis™, Bayer Crop Science LP) on August 1, 2013 (36 days after planting).

3.3.3 Field Data Collection

All plant and soil data were collected from the center four rows of each plot. Plant heights and stand count was measured in a randomly selected 1 m section of row duplicated in each plot. During 2012, this was done bi-weekly, while in 2013 the frequency was increased to weekly. This was done due to a concern that the temporal spacing was too coarse to capture plant growth differences in 2012. Following the *"United States Standards for Grades of Sweet Corn for Processing"*, the harvested corn was selected for harvested at 76% moisture, in the milk stage, on average at least three to four inches of harvestable kernels with similar color (USDA, 1997). In 2012, *Ambrosia* and *Protégé* was harvested on September 6th (76 days after planting) and *Overland* was harvested on September 11th (81 days after planting) In 2013, *Ambrosia* and *Protégé* were harvested on September 9th (75 days after planting) and *Overland* on September 11th (77 days after planting). During harvest, percent kernel moisture, unhusked ear weight, husked ear weight, weight of cut corn, ear length, ear circumference, unfilled tip, and overall marketability were recorded. Sweet corn data was collected based on a sample of ten randomly selected ears per plot. Percent kernel moisture was determined using gravimetric dry weight in which the corn was dried at 105 ^{o}C for 24 hours. Ear marketability was determined by considering ear qualities including uniformity and kernel fill of these ten selected ears from each plot. Additionally, five different sugar contents (sucrose, glucose, fructose, maltose, and lactose), kernel micro and macro nutrients, and other kernel properties were analyzed (Midwest Laboratories, Omaha, NE) from a homogenized shelled sample of these 10 ears from each plot. The sugars were analyzed with association of analytical communities (AOAC) 982.14 method (AOAC, 2000), and the nutrients were analyzed with by AOAC 985.01 procedure (AOAC, 2000).

Soil sampling was conducted annually after harvest to assess differences in soil chemical properties. However, in 2012 limited sampling was conducted due to the fact that changes were not expected within the one year time period. Sampling consisted of homogenizing all treatment replicates (across blocks) into one soil sample representing each treatment. In 2013, each individual plot was sampled by compositing a 0-5 cm surface sample (2.54 cm diameter soil core) from 3 row and 3 between rows (furrow) locations in each plot. This homogenized sample was assumed to be representative of the individual treatment plot. The soil samples were analyzed in the St. Paul, MN laboratory for total C and N (Elementar varioMAX CN analyzer; Elementar Americas Inc., Mt. Laurel, NJ) and sent to a commercial soil lab for standard macro- and micro-nutrient analysis following Soil Science Society of America recommendations (A & L Analytical Labs, Memphis, TN).

To assess differences in air temperature between the years, growing degree days (GDD) will be utilized. GDD is a means for expressing total heat accumulation above a certain threshold temperature (base temperature). Calculating GDD for a specific day uses a simple formula that involves subtracting a base or threshold temperature from the average temperature for the day Equation 3.1 is used to calculate the GDD for the period after planting:

$$GDD = \sum\left(\frac{T_{\max} - T_{\min}}{2}\right) - T_B \,, \tag{Eq. 3.1}$$

where T_B is the base temperature which is a function of the crop being considered. The base temperature is the minimal temperature for which plant growth occurs and varies as a function of crop and hybrid (Moreno et al., 2014). The typical base temperature for sweet corn is 10^oC (McMaster and Wilhelm, 1997). This allowed the air temperature differences to be compared referenced to the same basis.

3.3.4 Statistical analysis

The data presented are the means of randomly selected 10 ears per plot, and presented as the means of the 3 treatment replicates for each variety, unless specified otherwise. The main effects of variety, tillage, and year were analyzed through general linearized model and analysis of variance. I utilized both R (R, 2008) and JMP (Version 11; SAS Institute Inc., Cary, NC) for these analyses. Within R, the *lm*() command was used for the linear modeling and the *aov*() command for the ANOVA analysis of the linear model. A statistically significant difference was assumed to be at the 95% confidence interval ($P<0.05$). Cut corn is highly correlated ($R>0.75$) with other assessments of sweet corn productivity which were also measured of unhusked ear, husked ear, ear length, ear circumference, and percent marketability across both years (Figure A1). Therefore, cut corn will be used as the assessment of sweet corn yield in the study. In the overall data correlations, ear height is not correlated with percent ear marketability and unfilled tip. Also, unfilled tip is not correlated with harvest moisture (Figure A1). Stalk biomass, harvest moisture, ear height, and unfilled tip are weakly correlated with the other sweet corn properties, as expected. Kernel phosphorus is correlated ($R>0.80$) with the other kernel nutrients tested, but not the kernel sugar contents. Kernel sucrose content, kernel C:N ratio, and kernel nutrients were not closely influenced by any other kernel properties, so they were analyzed separately.

3.4 Results and Discussion

3.4.1. Climate

From 1971 to 2000, the 30 year average annual precipitation for Rosemount, MN was 879 mm (MRCC, 2014). During 2012, the annual precipitation was 823 mm, and during 2013, it was 799 mm (Figure 3.2; Griffis and Baker, 2014). This amounts to a 6.3% and 9.1% reduction compared to the 30 year average, respectively in 2012 and 2013. Figure 3.3 illustrates the cumulative precipitation in the two years following planting date in each year. As seen in the graph, the summer of 2012 was a slightly drier than an average year (Figure 3.2), yet the sweet corn crop received enough rain when it was needed it, and there were no visible signs of drought stress (Figure 3.3). In 2012, there was an even precipitation distribution from 20 days after planting to day 50. On the other hand, the sweet corn did exhibit visible signs of drought stress in 2013. Even though the overall precipitation pattern is similar (Figure 3.3), the rain events in 2013 were more sporadic and of differing intensities. There was an earlier rain in 2013 after planting followed by 3 significant rain events with longer gaps between the precipitation events (particularly between 18-42 DAP and 42-80 DAP) compared to 2012. In addition, the 2013 growing season was overall drier than 2012, and little rain was received during the 35 days before harvest (Figure 3.3).

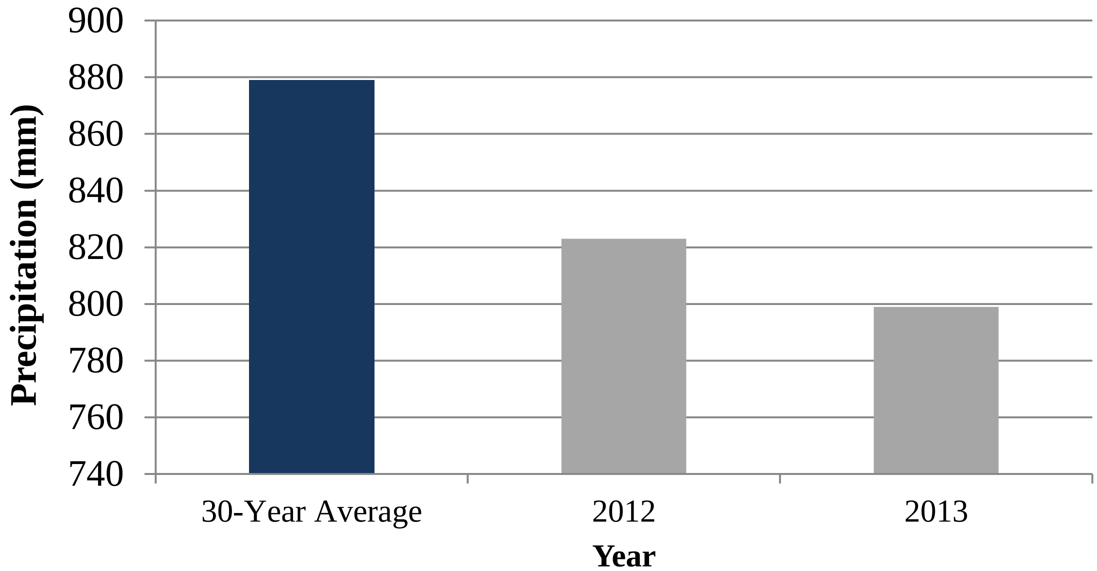

Figure 3.2 Average precipitation received from 1971 to 2000 in Rosemount, MN compared to the total annual precipitation in 2012 and 2013.

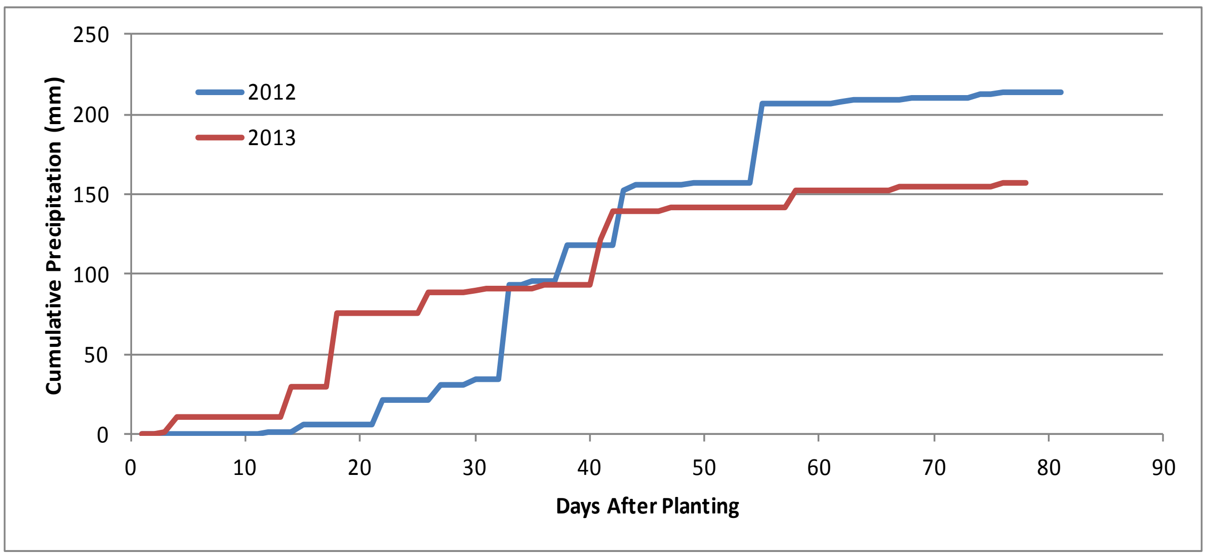

Figure 3.3 Cumulative precipitation (mm) for the period from planting to harvest for both 2012 and 2013.

The measured air temperature at the site for 2012 and 2013 is shown in Figures 3.4 and 3.5, respectively. Figure 3.6 illustrates the GDD for each of the 2 year field study. Similar to precipitation, there were differences between the GDD accumulations in the two field years. In general, 2013, was slightly cooler particularly in the period of 30-80 DAP (Figure 3.6). These lower temperatures potentially assisted in masking some of the drought stress, since warmer temperatures compounded with drought stress increase sweet corn yield losses (Lobell et al., 2011).

Considering both the lower than average precipitation and variable temperatures that were experienced during the 2012 and 2013 growing seasons, one would expect differences to be manifested in sweet corn quality as a result of this climate variability (Björkman et al., 1998; Duke and Doehlert, 1996; Oktem et al., 2003; Stone et al., 2000). One of the major concerns of field experiments is that no two growing seasons are identical in the design of a field experiment. However, this variability also enables the evaluation of the potential benefits of different management strategies in light of these climatic differences.

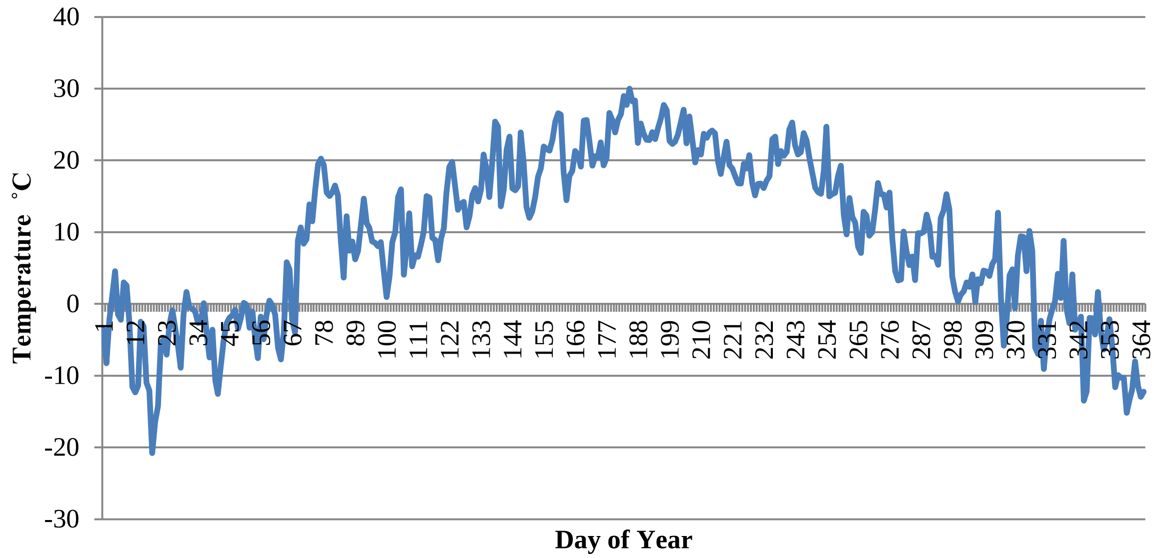

Figure 3.4 Air temperature recorded during 2012 at the Rosemount, MN field site.

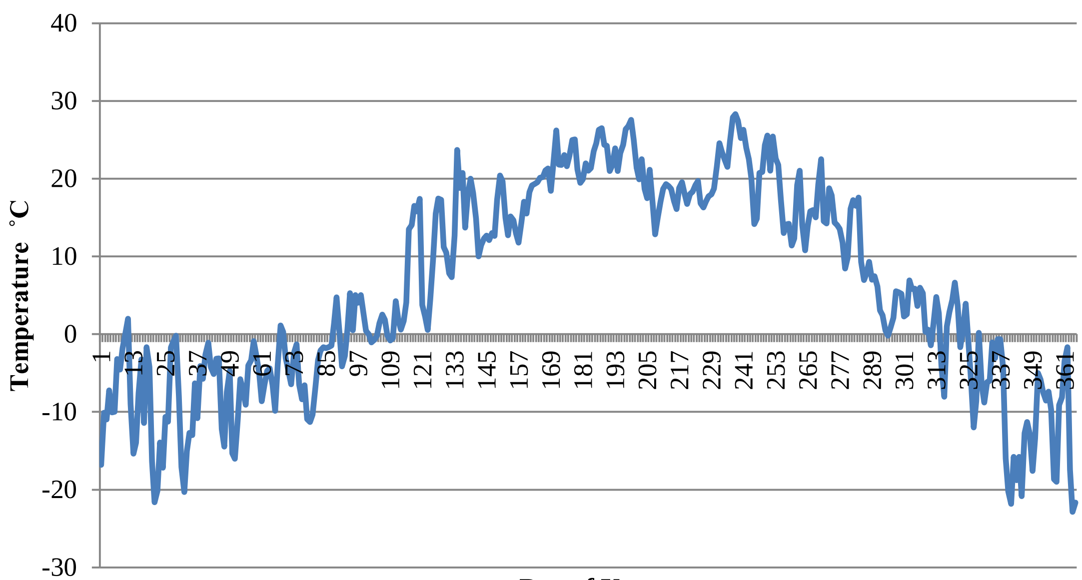

Figure 3.5 Air temperature recorded during 2013 at the Rosemount, MN field site.

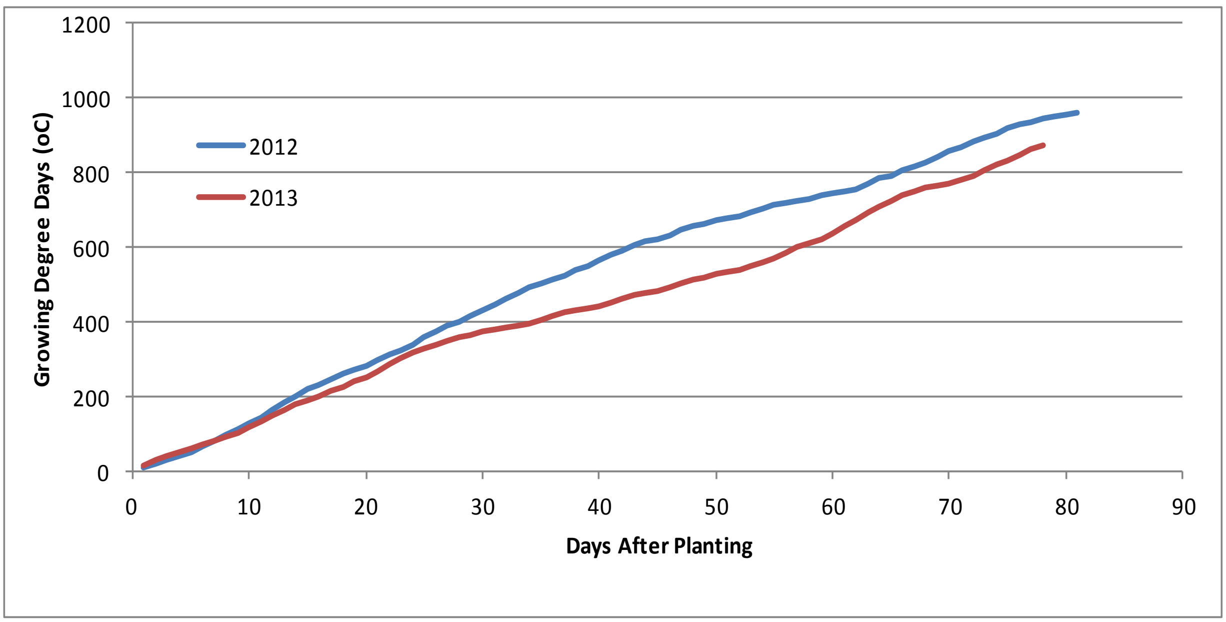

Figure 3.6 Comparing cumulative Growing Degree Days (GDD) for the period from planting to harvest for both 2012 and 2013.

3.4.2. Cut Corn Yield

Cut corn yield was influenced by tillage and year ($P<0.05$ and $P<0.001$, respectively; Table 3.1). Interestingly, there were not any observed variety impacts as a function of tillage on cut corn yield in this experiment (Table 3.1), with average yields for *Overland* of 5.3 Mg/ha, *Protégé* with 5.2 Mg/ha, and *Ambrosia* with 5.8 Mg/ha across the different tillage types and years (Table 3.2). In addition, there were no significant two- or three-way interactions between the factors (tillage, variety, and year) on cut corn yield in this experiment (Table 3.1). Ridge tillage resulted in a 17% greater cut corn yield when compared to conventional till across the varieties and years (Table 3.2). In two similar studies, ridge tillage did not adversely affect yield of sweet corn of two different sweet corn varieties (Makus, 2000, Makus, 2002), but these studies did not observe any increases in yield from ridge tillage use. This could be attributed to the fact that these studies utilized supplemental irrigation, since they were located in a subtropical environment. Thereby, this irrigation could negate the benefitial impact of ridge tillage compared to conventional tillage on soil moisture and potentially yield increases. Haghighat et al. (2012) observed higher yields from sweet corn planting in furrows rather than ridges, but the physical description of this cropping system was not fully given. Bakht et al. (2011) perceived higher total above ground biomass from sweet corn grown under ridge and raised beds, as opposed to broadcast and conventional (line) planting. This increase in yield resulting from ridge tillage has been typically observed in more arid countries (Belachew and Abera, 2010; Arif et al., 2001; Siddique and Bakht, 2005). This has also been the result when field corn and soybean rotations are grown using ridge tillage when compared to conventional tillage (e.g., He et al., 2010). Together, all these results suggest that ridge tillage does indeed provide an improved plant growth environment and enhanced nutrient/soil moisture avaiability in a moisture stressed environment.

The greater observed yield in ridge till plots may be partially due to the physical alteration in the soil properties under ridge tillage that enhances soil water retention and availability (Section 1.4). In 2013, there was visible drought stress observed which correspondingly reduced yields by 65% across all varieties (8.0 Mg/ha in 2012 and 2.8 Mg/ha in 2013; Table 3.2). The conventional tillage yield was reduced by 5.4 Mg/ha, where the ridge tillage was reduced only by 5 Mg/ha (Table 3.2); a difference of approximately 10%, which is similar to decreases observed in other studies (e.g., Oktem, 2008). It is known that growing corn using ridge till may be more environmentally sustainable in the long term when compared to conventional till (Hatfield et al., 1998; He et al., 2010; Pikul et al., 2001). The data collected here supports the concept that ridge tillage also provides an increased buffering capacity to climate variability, particularly precipitation differences, in limiting yield declines compared to conventional tillage.

Table 3.1 P-values of main effects and interactions of sweet corn performance components analyzed through the analysis of variance of cut kernel yield, sucrose content, kernel C:N ratio, and kernel phosphorus.

	Cut corn yield	Kernel C:N ratio	Kernel sucrose content	Kernel Phosphorus
Main Effects				
Tillage	*			
Variety		***	***	***
Year	***	***	***	***
Interactions				
Variety × *Tillage*		***		
Variety × *Year*		***	***	***
Tillage × *Year*				
Variety × *Tillage* × *Year*		***		

Note: Interactions indicated with a ***, **, and * are statistically significant at α = 0.001, 0.01, and 0.05; blank cells are non-significant interactions.

Table 3.2 Means of main effects and interactions of cut kernel yield, sucrose content, kernel C:N ratio, and kernel phosphorus.

		Cut corn yield Mg/ha	Kernel C:N ratio	Kernel sucrose content % dry weight	Kernel P % dry weight
Main Effects					
Tillage					
	Conventional	4.9 a	21.3 a	19.2 a	0.3 a
	Ridge Till	5.9 b	21.1 a	20.2 a	0.2 a
Variety					
	Overland	5.3 a	19.7 a	25.5 a	0.2 a
	Protégé	5.2 a	21.3 b	19.0 b	0.3 b
	Ambrosia	5.8 a	22.8 c	14.6 c	0.2 a
Year					
	2012	8.0 a	20.1 a	9.0 a	0.4 a
	2013	2.8 b	22.5 b	31.1 b	0.1 b
Interactions					
Variety × Tillage	Overland - Conventional Tillage		21.5 ab		
	Overland - Ridge Tillage		17.9 b		
	Protégé - Conventional Tillage		21.4 ab		
	Protégé - Ridge Tillage		21.2 ab		
	Ambrosia - Conventional Tillage		21.2 ab		
	Ambrosia - Ridge Tillage		24.3 a		
Variety × Year	Overland - 2012		19.6 a	19.0 a	0.4 b
	Overland -2013		19.8 a	32.1 b	0.1 d
	Protégé - 2012		21.7 a	5.6 a	0.4 a
	Protégé - 2013		20.8 a	35.1 b	0.1 d
	Ambrosia - 2012		19.0 a	2.5 a	0.4 c
	Ambrosia - 2013		26.5 b	26.7 b	0.1 d

Note: Mean values followed by the same letter are statistically equal (P<0.05), and those with different letters are significantly different (P<0.05).

3.4.3. Kernel C:N Ratio

Despite the significant difference in yield, surprisingly tillage did not influence kernel C:N ratios, but variety and year did significantly influence kernel C:N ratios ($P<0.001$; Table 3.1). Additionally, both two-way-interactions of *variety x tillage* and *variety x year* were significant ($P<0.001$), as well as the three-way-interaction of *variety x tillage x year* ($p<0.001$). These interactions indicate that there are differences in how varieties of sweet corn respond to both tillage and precipitation differences (year). *Overland* grown using conventional till was observed to have 20% greater kernel C:N than that grown using ridge tillage (Table 3.2). *Ambrosia* grown in ridge till had a 15% greater kernel C:N ratio than *Ambrosia* grown in conventional tillage (Table 3.2). Interestingly, *Protégé* C:N content was not a function of tillage (Table 3.2).

There were no consistent trends observed in this study based on *variety x tillage* interactions (Table 3.2) Other studies have also observed no significant differences in C:N ratios at harvest (Brinton, 1985). Potentially, this could have been overcome if additional tissue samples were taken at different times through this study rather than just at harvest (Briton, 1985). A stated benefit of ridge tillage has been soil water availability (Zibilske and Bradford, 2007), but the lack of significant differences in the C:N content observed in this study could also be due to the fact that this was a two-year study and the ridges were produced in the first experimental year. Therefore, additional time might be required in order for the benefits of ridge tillage to manifest observable differences in soil structure (Zhang et al., 2012) and plant available nutrients, which eventually may be reflected in kernel C:N ratios (Clay et al., 1995; Hatfield et al., 1998; Nokes et al., 1997; Shi et al., 2012).

On the other hand, variety and year significantly ($P<0.001$) influenced kernel C:N ratio (Table 3.1). Varying kernel C:N ratio was expected among varieties, due to genetic differences. The different kernel C:N ratios of 2012 and 2013 are noteworthy though, in which the 2013 growing season had 12% higher kernel C:N than 2012 (Table 3.2). Correspondingly, 2013 experienced reduced soil water availability as discussed earlier (Section 3.4.1). Contrastingly, Zhu et al. (2007) found that field corn kernels had a lower N content and higher C content with surface drip irrigation as a treatment compared to non-irrigated plots, such that the irrigated plot kernels had a statistically higher C:N ratio. Conversely, there are no negative impacts of tillage on kernel C:N ratio as a consequence of ridge tillage.

3.4.4. Kernel Sugar Contents

Similar to the kernel C:N, variety and year significantly influenced kernel sugar contents ($p<0.001$; Table 3.1). Additionally, a two-way-interactions of *variety x year* were significant ($p<0.001$) for kernel sugars (Table 3.1). These interactions indicate that there are differences in the sugar contents of the different varieties as well as how the sugar content of the varieties of sweet corn respond to precipitation differences (year). For the varieties, *Overland* had a sucrose content of 25.5%, *Protégé* was 19.0%, and *Ambrosia* was 14.6% (dry wt basis) (Table 3.2). In addition, the 2013 kernels possessed a significantly higher sugar content (31%) compared to that in 2012 (9%), which was also a function of the variety, with *Protégé* having the highest increase of 6.3 times in 2013. (Table 3.2)

Kernel sugar was investigated in this study to see if tillage can affect kernel sugar contents, since sweetness is the most dominant factor used to determine sweet corn flavor and quality (Dickert and Tracy, 1997; Reyes et al., 1982). Among the sugars found in sweet corn, sucrose is the prominent and best predictor of the sweetness perception of sweet corn flavor (Hale et al., 2005; Wong et al., 1994). Sucrose content was strongly correlated with glucose, and fructose content (Figure A1), so the kernel sucrose trends discussed apply overall to glucose and fructose unless specified otherwise. The maltose and lactose sugar content data are shown, but not discussed further because they are minor kernel sweetness predictors.

Contrary to the hypothesis, tillage type did not influence kernel sugar contents. Yet, sweet corn kernel sucrose content was significantly ($P<0.001$) influenced by variety and year in addition to the *variety x year* interactions ($P<0.001$) (Table 3.1). The 2013 growing season was observed to have more kernel sucrose when compared to 2012 (246% higher), which is the most significant sucrose difference observed in this study (Table 3.2). Similarly, Dickert and Tracy (1997) found that reduced irrigation increased sucrose content when compared to a standard irrigation treatment. This observation could partly explain the greater sucrose observed in this study, since there was lower total precipitation in 2013, with 823 mm and 799 mm of precipitation in 2012 and 2013 (Section 3.4.1).

It should be noted that for both years, the sugar contents were higher than the typical range of sweet corn sugar content based on data compiled by Headrick et al. (1990) (Table 3.3). Specifically, the range of average sucrose concentration in Headrick et al. (1990) is 12 to 32.7 mg g^{-1} of dry kernel weight, but the sucrose content of the sweet corn kernels of this study were 90 and 311 mg g^{-1} dry weight, for 2012 and 2013, respectively. This trend is observed among the other sugars as well. The glucose range found in Headrick et al. (1990) is 0.2 to 7.0 mg g^{-1} and this study observed 31.0 to 314 mg g^{-1}. Also, the fructose range found in Headrick et al. (1990) is 0.1 to 6.0 mg g^{-1} and this study observed 39.0 to 76.0 mg g^{-1}.

Table 3.3 Ranges and mean values of sweet corn kernel sugar concentrations comparing data from (Headrick et al., 1990) and this study.

Sugar	Range of average concentration from (Headrick et. al, 1990) [mg/g of dry kernels]	Range of average concentration of this study [mg/g of dry kernels]
Sucrose	12.0 – 32.7 (23.2)	17.5 – 386.0
Glucose	0.2 – 7.0 (1.9)	31.0 – 314.0
Fructose	0.1– 6.0 (1.2)	39.0 – 76.0
Maltose	0.0 – 2.6 (0.7)	0.0 – 19.0
Lactose	Not specified	0.0 – 6.1
Total Sugar Contents	15.1 – 46.0 (27.1)	87.5 – 801.1

3.4.5. Kernel Nutrients

Similar to the kernel C:N and sugar contents, kernel phosphorus (P) was significantly influenced by the variety and year of this experiment, as well as the two-way-interaction of *variety x year* ($P<0.001$; Table 3.4). These interactions indicate that there are differences in the kernel P content as a function of the variety as well as how the P content of the varieties respond to precipitation differences (years). In terms of varieties, *Protégé* had 50% greater kernel P than *Overland* and *Ambrosia* (Table 3.5). During 2012, kernel P was observed to be 400% greater in 2013 (Table 3.5).

Tillage significantly impacted solely kernel Ca and Na ($P<0.001$) (Table 3.4). However, this difference was not numerically meaningful (i.e., 0.004 to 0.002%), given the reporting range for these nutrient analysis from the laboratory (% dry weight). Sweet corn variety influenced kernel P, K, Ca, Na, and Fe ($P<0.001$) and kernel S, Mg, and Zn ($P<0.01$) (Table 3.4). However, Mn and Cu kernel contents were not a function of variety (Table 3.4). Universally, the year influenced all the assessed kernel nutrients ($P<0.001$; Table 3.4). The two-way *variety x year* interaction influenced kernel P and K at ($P<0.001$) and Mg at ($P<0.05$), indicating that there were differences due to year as a function of variety (Table 3.5).

These observations were a bit surprising, since other studies have observed differences in kernel contents as a function of management decisions. Bierman and Rosen (1994) evaluated sewage sludge incinerator ash as a P fertilizer and determined trace mineral availability, in which they did observe statistical differences as a function of fertilizer additions. It has been observed previously that the Fe, Zn and Cu concentration of sweet corn kernels decrease with increasing water deficiency (Oktem, 2008). Warman and Havard (1998) analyzed sweet corn kernel properties and observed similar nutrient values across conventional and organic production treatments. Warman and Havard (1998) concluded that climate variations have a greater influence on plant production than the source and amount of applied compost in the long-term. However, Makhlouf et al. (1995) cautioned that sweet corn kernel nutrients should be used with care, in particular to the conclusions drawn from them.

Therefore, the data collected was contrary to the initial hypothesis that there would be nutrient differences in sweet corn kernels as a function of tillage treatment. This was based on the fact that the postulated soil moisture differences could lead to different nutrient availability between the plots. The experimental data shows that these nutrient effects were not manifested in the first two years of the study and longer term plots might be needed to fully assess these differences. Therefore, the main conclusion from the kernel nutrition is that there were no negative effects observed from ridge tillage.

Table 3.4 P-values of main effects and interactions of kernel nutrients analysis of variance.

	S	P	K	Mg	Ca	Na	Fe	Mn	Cu	Zn
Main Effects										
Tillage					***	***				
Variety	**	***	***	**	***	***	***			**
Year	***	***	***	***	***	***	***	***	***	***
Interactions										
Variety × Tillage										
Variety × Year		***	***	*						
Tillage × Year										
Variety × Tillage × Year										

Note: Interactions indicated with a ***, **, and * are statistically significant at $\alpha = 0.001$, 0.01, and 0.05; blank cells are non-significant interactions.

Table 3.5 Means of main effects and interactions of kernel nutrients at harvest.

		S	P	K	Mg	Ca	Na	Fe	Mn	Cu	Zn
Main Effects				% dry weight					ppm		
Tillage	*Conventional*	0.1	0.3	0.8	0.1	0.0 a	0.0 a	15.2	4.7	1.6	15.6
	Ridge Till	0.1	0.2	0.7	0.1	0.0 b	0.0 b	13.7	4.5	1.8	15.2
Variety	*Overland*	0.1 a	0.2 a	0.7 a	0.1 a	0.0 a	0.0 a	12.4 a	4.5	1.8	15.3 a
	Protégé	0.1 b	0.3 b	0.9 b	0.1 b	0.0 b	0.0 b	13.2 a	4.7	1.7	16.7 b
	Ambrosia	0.1 a	0.2 a	0.7 a	0.1 a	0.0 a	0.0 a	17.5 b	4.7	1.6	14.2 a
Year	*2012*	0.2 a	0.5 a	1.3 a	0.1 a	0.0 a	0.0 a	26.6 a	7.2 a	3.3 a	24.6 a
	2013	0.0 b	0.1 b	0.2 b	0.0 b	0.0 b	0.0 b	1.5 b	1.8 b	0.1 b	5.7 b
Interactions											
Variety × Year	**Overland - 2012**		0.4 b	1.3 b	0.2 a						
	Overland -2013		0.1 d	0.2 d	0.0 c						
	Protégé - 2012		0.4 a	1.4 a	0.2 a						
	Protégé - 2013		0.1 d	0.2 d	0.0 c						
	Ambrosia - 2012		0.4 c	1.1 c	0.1 b						
	Ambrosia - 2013		0.1 d	0.2 d	0.0 c						

Note: Mean values followed by the same letter are statistically equal (P<0.05), and those with different letters are significantly different (P<0.05).

3.4.6 Soil Properties

The soil properties of organic matter, CEC, pH, and buffer pH were not influenced by tillage or year, or the two-way-interaction of *tillage x year* with one exception (Table 3.6). The soil CEC was significantly influenced by year ($P<0.05$), with a 12% increase was observed in 2013. Among the soil nutrients analyzed, Cu, B, and Cu was statistically influenced by year ($P<0.05$) (Table 3.6). Specifically, Cu and B were higher at the start of the study by 31% and 75%, respectively (Table 3.7). Calcium was the only nutrient that was 10% higher at the end of the study, but the exact cause of this is unknown (Table 3.7).

In this study, the soil data was collected to assess if there was any difference in soil properties as a function of the tillage treatments during the 2 years, but there was no conclusive differences (Table 3.7). Soil C:N ratio is always changing based on the soil properties, input organic matter C:N ratio, the soil microorganisms that break down the residue, and the climate of the area (NRCS, 2011). It is difficult to draw a robust long-term conclusion from this soil data, but it does illustrate that there were no negative impacts of ridge tillage over the 2 year field study.

Soil nutrient cycling is an intricate process of balancing mineralization and residue inputs that are based on biological cycling, weathering, leaching, and atmospheric deposition (Jobbagy and Jackson, 2001). Further complicating this are the phase changes minerals go through during individual nutrient cycles specific only to that nutrient (Stevenson and Cole, 1999). As discussed in Section 1.4, ridge tillage allows for different zones of soil processes to develop in the field, which over time soils can alter the accumulation of nutrients available for crop uptake (Kanwar et al., 1997). Additional time could be required in order for the benefits of ridge tillage to manifest observable differences in soil properties (Zhang et al., 2012, Clay et al., 1995; Hatfield et al., 1998; Nokes et al., 1997; Shi et al., 2012). It is difficult to draw a robust long-term conclusion from this soil data, but it does illustrate that there were no negative impacts of ridge tillage over the 2 year field study on soil properties.

Table 3.6 P-values of main effects and interactions of soil macro- and micro- nutrient analysis of variance.

	OM	CEC	pH	Buffer pH	P	K	Ca	Mg	S	Na	Zn	Mn	Fe	Cu	B
Main Effects															
Tillage															
Year		*					*							***	***
Interactions															
Tillage x Year															

Note: Interactions indicated with a ***, **, and * are statistically significant at α = 0.001, 0.01, and 0.05; blank cells are non-significant interactions.

Table 3.7 Means of main effects and interactions of soil properties.

	Organic matter	CEC	pH	P	K	Ca	Mg	S	Na	Zn	Mn	Fe	Cu	B
									(ppm)					
Main Effects														
Tillage														
Conventional	4.4	13.7	5.8	99.2	317.0	1783.8	381.2	27.6	19.2	3.5	95.8	165.8	1.8	0.5
Ridge Till	4.5	14.8	5.6	124.6	394.6	1846.2	408.0	40.2	19.6	3.8	115.2	177.2	1.8	0.5
Year														
2012	4.3	**13.3 a**	5.8	103.5	343.8	**1715.0 a**	372.3	30.0	19.0	3.6	92.8	173.0	**2.1 a**	**0.7 a**
2013	4.6	**14.9 b**	5.7	117.5	363.8	**1881.7 b**	409.5	36.5	19.7	3.7	114.0	170.5	**1.6 b**	**0.4 b**
Interactions														
Tillage × Year														
Conventional Tillage - 2012	4.2	13.1	5.8	101.0	345.0	1671.5	367.0	22.0	17.5	3.5	87.5	174.0	2.1	0.7
Conventional Tillage - 2013	4.5	13.6	5.7	106.0	342.5	1758.5	377.5	38.0	20.5	3.8	98.0	172.0	2.1	0.7
Ridge Tillage - 2012	4.6	14.2	5.8	98.0	298.3	1858.7	390.7	31.3	20.3	3.5	101.3	160.3	1.6	0.4
Ridge Tillage - 2013	4.6	15.6	5.6	137.0	429.3	1904.7	428.3	41.7	19.0	3.8	126.7	180.7	1.6	0.4

Note: Mean values followed by no letter or the same letter are statistically equal ($P<0.05$), and those with different letters are significantly different ($P<0.05$).

3.5 Conclusions

In light of the variable climate experienced during this study, especially limited precipitation during 2013, the data suggests that ridge till can be advantageous for sweet corn production in Minnesota providing a means to buffer climatic variability. As seen with the cut corn yields and percent marketability, *Protégé* may adapt better to ridge tillage when compared to other sweet corn varieties. Further investigation could be done to analyze the genetic traits of *Protégé* and how that variety interacts with tillage practices. During 2012, there was minimal significant difference noted between ridge and conventional tillage treatments. However, during a drier than average year, such as 2013, sweet corn grown under ridge till had greater cut corn weight, ear marketability, and sucrose content than the corresponding conventional tillage practices. This data also suggests additional long term benefits that were not adequately captured in this 2 year study.

Chapter 4 - Conclusions

The effect of biochar application and weathering on seed emergence, seedling growth, and crop yield depends on a complex interaction of soil and biochar properties, amendment rates, and the specialty crops grown. Negative emergence and seedling growth impacts were usually observed fast pyrolysis macadamia nut shells. The wood pellet and corn cob slow pyrolysis biochars typically had positive impacts at the 5% amendment rate, with the corn cob derived biochar performing the best at this rate for improving seed emergence and initial plant growth across all soil types. However, plant growth was increased most consistently on sandy textured soils. This supports the conclusion that biochar applications may increase crop productivity due to greater seed emergence and enhanced seedling growth, when applied to target a specific soil deficiency including moisture and nutrient holding capacities.

It takes time for ridges to develop and advantages soil properties associated with conservation ridge tillage to manifest in crop production. In light of the variable climate experienced during this study, specifically precipitation, the data suggests that ridge till can be advantageous for sweet corn production. During a drier than average year, such as 2013, sweet corn grown under ridge till may have greater cut corn weight, ear marketability, and sucrose content. In addition to this, both soil and kernel nutrient and C/N ratios were not negatively impacted by ridge till. Also, specific sweet corn varieties, in this case *Protégé*, may perform better than others when grown under ridge till conditions when all other environmental controls are kept constant.

Increasing crop residency to variable climates by using biochar as a soil amendment, targeting a soil deficiency such as moisture or nutrient holding capacity, or utilizing ridge tillage to enhance soil moisture retention seems to not have any negative impacts. Hopefully this study will help specialty crop producers make sound decisions if they are considering applying biochar trying ridge tillage. It would also be interesting to determine if biochar applied in ridge till crop production system has an impact on soil properties, and on crop seed emergence, growth, and yield.

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Appendix

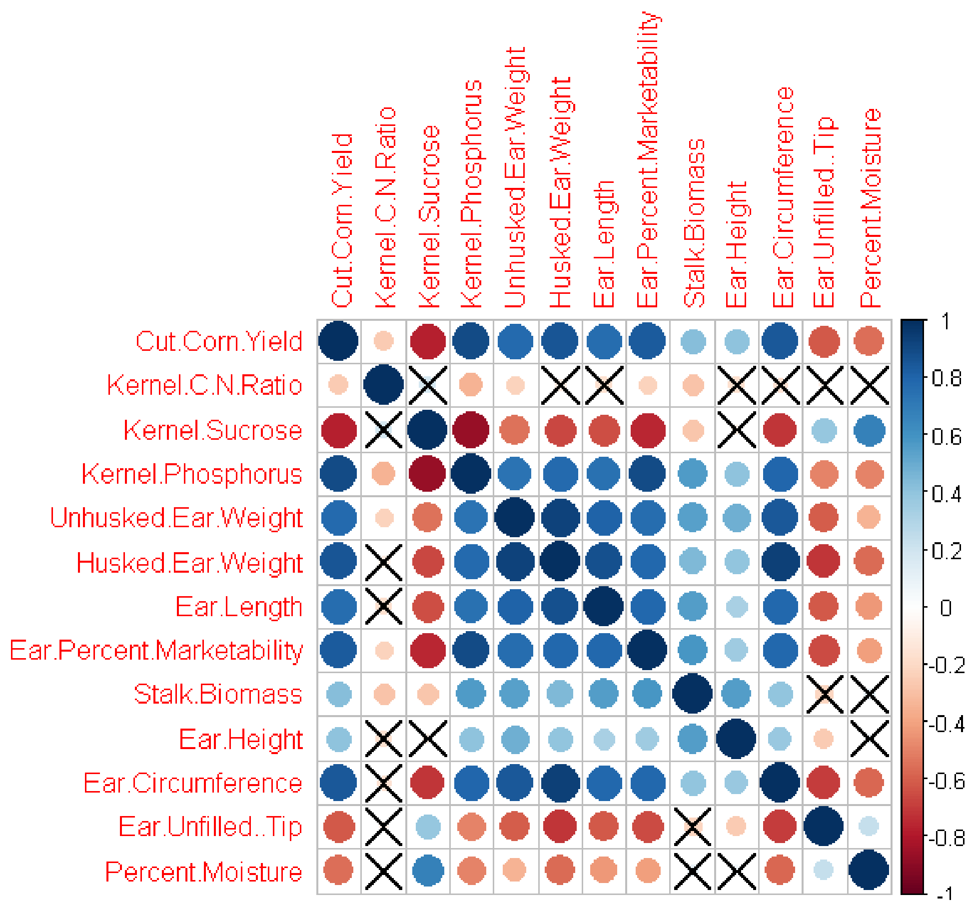

Figure A.1 Overall sweet corn data correlations. Cut corn is highly (R>0.75) correlated with other assessments of sweet corn productivity which were also measured of unhusked ear, husked ear, ear length, ear circumference, and percent marketability across both years. An "X" indicates a non-significant correlation (P>0.05).

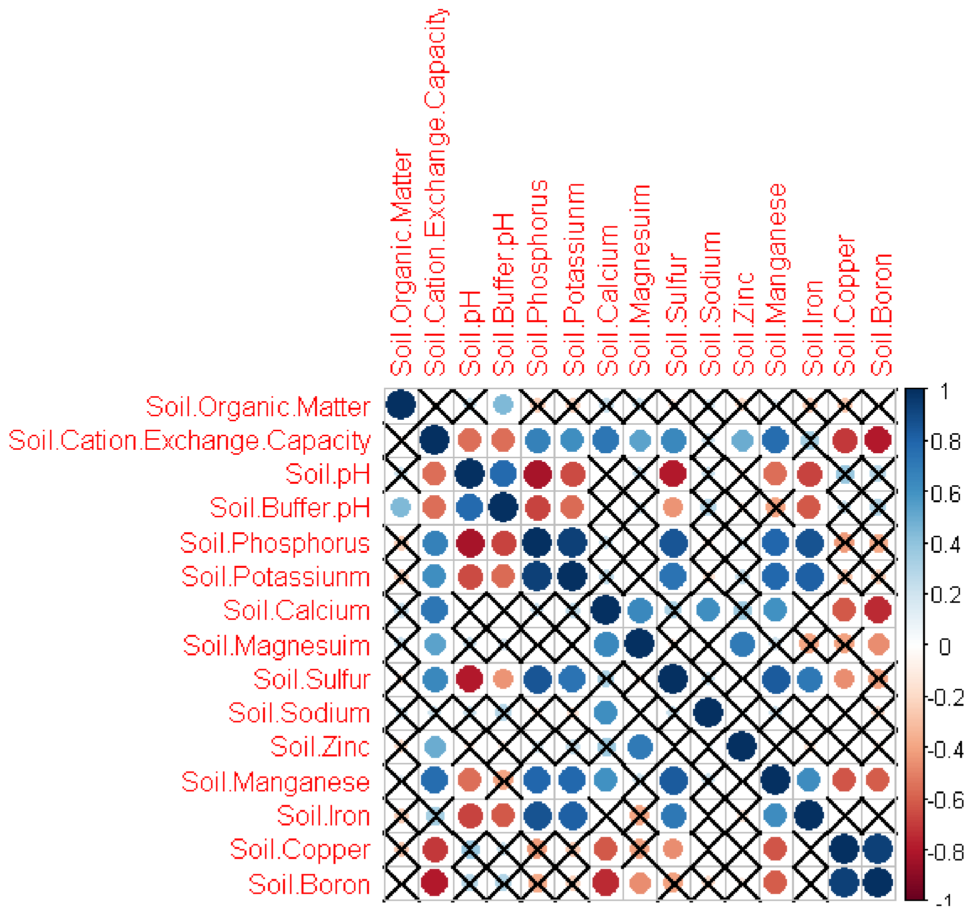

Figure A.2 Overall soil data correlations. An "X" indicates a non-significant correlation (P>0.05).

Table A.1 Main effects and interaction values of sweet corn performance components analysis of variance of cut kernel yield, sucrose content, kernel C:N ratio, and kernel phosphorus.

	Cut Corn Yield	Sucrose Content	Kernel C:N Ratio	Kernel Phosphorus
Main effects				
Tillage	3.1	1.0	0.6	0.0
Variety	1.1	1.9	5.3	0.1
Year	15.6	12.5	7.1	1.0
Interactions				
Variety × Tillage	1.5	0.1	5.8	0.0
Variety × Year	2.1	4.1	7.9	0.1
Tillage × Year	0.6	0.5	0.3	0.0
Variety × Tillage × Year	0.4	0.5	6.0	0.0

Table A.2 Main effects and interaction values of kernel sugars analysis of variance

	Sucrose	Glucose	Fructose	Maltose	Lactose
Main effects					
Tillage	1.0	0.4	0.1	0.4	0.0
Variety	2.0	3.0	0.1	1.4	0.0
Year	12.5	7.9	0.4	2.1	0.3
Interactions					
Variety × Tillage	0.1	0.1	0.1	0.4	0.0
Variety × Year	4.1	2.7	0.2	1.3	0.0
Tillage × Year	0.4	0.1	0.1	0.5	0.0
Variety × Tillage × Year	0.5	0.3	0.1	0.4	0.0

Table A.3 Main effects and interaction values of kernel nutrients

	S	P	K	Mg	Ca	Na	Fe	Mn	Cu	Zn
Main effects										
Tillage	0.0	0.0	0.1	0.0	0.0	0.0	4.7	0.4	0.4	1.0
Variety	0.0	0.1	0.4	0.0	0.0	0.0	9.3	0.5	0.4	4.3
Year	0.4	1.0	3.0	0.3	0.0	0.0	74.3	15.9	9.5	55.7
Interactions										
Variety × Tillage	0.0	0.0	0.1	0.0	0.0	0.0	0.7	0.1	0.2	1.6
Variety × Year	0.0	0.1	0.3	0.0	0.0	0.0	1.7	0.6	0.2	2.4
Tillage × Year	0.0	0.0	0.0	0.0	0.0	0.0	4.2	0.1	0.3	0.2
Variety × Tillage × Year	0.0	0.0	0.1	0.0	0.0	0.0	2.3	0.1	0.2	1.9

Table A.4 Main effects and interaction values of soil property analysis of variance before harvest

	Organic matter	CEC	pH	Buffer pH
Main effects				
Tillage	0.2	1.7	0.3	0.0
Year	0.4	2.4	0.1	0.0
Interactions	0.2	0.7	0.1	0.1
Tillage × Year	0.2	1.7	0.3	0.0

Table A.5 Main effects and interaction values of soil macro- and micro- nutrient analysis of variance before harvest

	P	K	Ca	Mg	S	Na	Zn	Mn	Fe	Cu	B
						ppm					
Main effects											
Tillage	40.2	122.7	98.7	42.4	19.2	0.6	0.5	30.7	18.0	0.1	0.0
Year	21.7	31.1	258.2	57.7	10.1	1.0	0.0	32.9	3.9	0.7	0.4
Interactions	26.3	103.4	31.8	21.0	4.4	3.4	0.1	11.5	17.3	0.0	0.0
Tillage × Year	40.2	122.7	98.7	42.4	19.2	0.6	0.5	30.7	18.0	0.1	0.0